Technical Review of Crop Yields Within Imperial Irrigation District

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Introduction

Water is an essential input to the production of crops and water use by crops is proportional to yield. The amount of water consumed by crops grown within Imperial Irrigation District (IID) has increased over time as a result of improvements in technology and farming practices which have enhanced the growing environment of the crops. Crops respond to the more favorable environment within farm fields by using more of the resources available to them for their growth and maintenance process. The result is greater yield and therefore greater beneficial water use. Since yields have increased dramatically in IID, it is correct to say that water beneficially consumed by the crop has also increased proportionally.

Water is used by the plant directly in the formation of cells and maintenance of the plant and to some extent the regulation of its immediate environment. The rate and manner of water use by vascular plants is governed by the ability of the plant to convert available solar energy to carbohydrates necessary for plant tissues. The plant must extract water from the soil and move it to the parts responsible for photosynthesis. Much of the plant's physiological process is therefore concerned with the uptake and loss of water.

The process of photosynthesis can be described as follows:

"When light of appropriate wavelengths is absorbed by a chloroplast (the primary physiological structure of the plant responsible for photosynthesis), carbon dioxide is chemically reduced to sugar, and gaseous oxygen, equal in volume to the CO_2 reduced, is liberated." In other words, the chloroplast possesses the ability to use energy from the sun to produce carbohydrates, a process which requires CO_2 and water as input and liberates oxygen as a by-product (Galston et.al, 1980). In order for a vascular plant to continue its physiological functions, water must be extracted from the soil and transported to the extremities of the plant, a process which is dependant on the plant maintaining a positive gradient (flow) of water from the roots to the photosynthesizing parts of the plant (mostly the leaf structures). As the sun provides energy for photosynthesis, it also provides for evaporation of water from the plant surfaces and in so doing determines the rate of evaporation of water from the leaf surfaces and through structures called stomata (controllable openings), a process referred to as transpiration. Other evaporation naturally occurs from the wet soil surfaces surrounding the plant. Together, the process is called evapotranspiration. Obviously water is a major input to the maintenance and growth of the plant. The plant's ability to use solar energy to transpire water, as part of photosynthesis and other water regulation functions within the cells of the plant, are a function of the type of plant, the environment of the plant, and the plant's vigor.

Crop Yield

Agricultural crop yields represent only a part of the total production of the agronomic plants grown because only portions of the plant are harvested. Tivy (1990) states that: "In both unmanaged ecosystems and agro-ecosystems biological productivity is expressed in terms of the rate of plant and/or animal biomass accumulated per unit land area within a specific time period. In both it is a function of the same basic process – photosynthesis – whereby simple inorganic elements (carbon, oxygen, hydrogen, nitrogen, potassium, phosphorous) derived from the atmosphere and the soil are converted, by chlorophyll-caring plant cells using light energy, into complex organic compounds (carbohydrates, proteins, fats). In both types of ecosystem the rate of plant growth (net primary productivity; NPP) is dependent, on the one hand, on the efficiency with which the available solar radiation is intercepted and used; and, on the other hand, on the difference between the rate of photosynthesis (gross primary productivity; GPP) and the rate of respiration (R) during which the energy used in plant metabolism is dissipated as heat, i.e.

$$NPP = GPP - R$$

Net primary production is usually recorded as the weight of dry matter production per unit area per unit time." "One of the principal aims of agriculture is to channel as much as possible of the energy from incoming solar radiation into selected crops and/or livestock, and to minimize that used by such potential competitors as weeds and pests."

Increases in Crop Yields

Yields of crops grown within IID have increased over the years. When considering yield data based on IID for the period of 1927 through 2001, it was found that the following increases in crops are evident:

1. Alfalfa yields increased eight-fold, from about 1.0 to 8.0 tons per acre.
2. Asparagus yields increased almost three-fold, from about 0.70 to 2.6 tons per acre.
3. Cantaloupe yields increased five-fold, from about 2.0 to 10 tons per acre.
4. Carrot yields increased nine-fold, from about 2.8 to 26 tons per acre.
5. Cotton Lint yields increased ten-fold, from about 0.1 to 1.0 tons per acre.
   Note: 1) the 1964 reported yield was believed to represent twice the reported acreage and was therefore reduced by half; 2) the 1966 reported yield was believed to be in error and was omitted.
6. Grapefruit yields increased ten-fold, from about 0.85 to 8.7 tons per acre.
7. Lettuce yields increased six-fold, from about 2.25 to 13.5 tons per acre.
8. Onion yields increased three-fold, from about 3.3 to 16 tons per acre, though onion yield has dropped off in the last 15 years.
9. Sudan Grass Hay yields have varied over the short history of records (1975 through 2001) yields have increased from 4.8 tons per acre, as in the first 10 years of record keeping, to 6.0 tons per acre.
10. Sugar beets yields have increased relatively stably from 1939 to the present for a two-fold increase, or from about 16.6 to 34 tons per acre.

11. Wheat yields in the early years of the project were very low, less than 1.0 tons per acre as recorded). It is assumed that factors such as yield efficiency was low. Using 1964 as a benchmark, wheat yields increased from about 2.6 tons per acre to about 3.2 tons per acre during the 1990s, representing a 1.2-fold increase in yield.

The combination of factors which affect crop production is an expression of the crop's growing environment. The farmer's field is therefore an integration of these factors which is managed specifically to maximize yield. When one or more factors are limiting to crop growth, less than maximum yields will be achieved. Water is considered the single most important factor limiting crop yields on a global scale (Tivy, 1990). For maximum production to take place, photosynthesis must occur at the maximum level and not be limited by availability of water and nutrients, nor negatively affected by temperature, or occurrence of weeds and pests. When all factors are not limiting, "Maximum photosynthesis occurs when the plant stomata (structures of vascular plants which open and close to regulate the rate of transpiration) are wide open, a condition dependent on a continuous supply of water to keep the guard cells turgid, and is normally attained when soil water is near, but just below, field capacity, i.e. when the soil water deficit is at a small but finite value of approximately 2.5 cm" (Monteith, 1977).

Increased yields of crops over the years within IID and elsewhere, are the result of crops trending toward maximum production as a result of better and more intensive management of farm units, including improvements in cultural practices, improved irrigation water distribution and reliability, increases in cropping intensity such as increased number of cuttings of alfalfa, double cropping and denser crop plant spacing, increases in fertilizer and pesticide use, and benefit from improved crop genetics resulting in higher pest resistance and greater plant density.

Causes of changes in yield, over time, are difficult to measure with regard to some of the specific factors affecting crop growth. For example, changes in genetically driven yield are estimated to be about 0.15-0.3% prior to the 1950s and about 1% for the period 1977-1992 based on trials conducted by Loiselle as reported by Wiersma (2002). Increased yields have, however, been dramatic over the years and fertilizer application has been estimated to have increased five-fold globally since the end of World War II (Tivy, 1990). IID farms are a good example of increased crop yields resulting from the cumulative effect of the increased intensity of crop management; they represent the development of an agricultural process which represents an optimization of crop selection and crop environmental factors which has generated remarkable increases in crop yields.

Figures 1 through 11 show these increases in yield for some of the crops grown within IID, including the major crops. These figures show historical crop yields of eleven crops and the presence and character of their yield trends. Historical crop and yield data were gathered from the Imperial Valley Agricultural Commissioner and IID for the years 1927 to 2001. Various statistics noted on the graphs come from University of California, A Guide Book to California Agriculture. These data were compiled for the following crops:

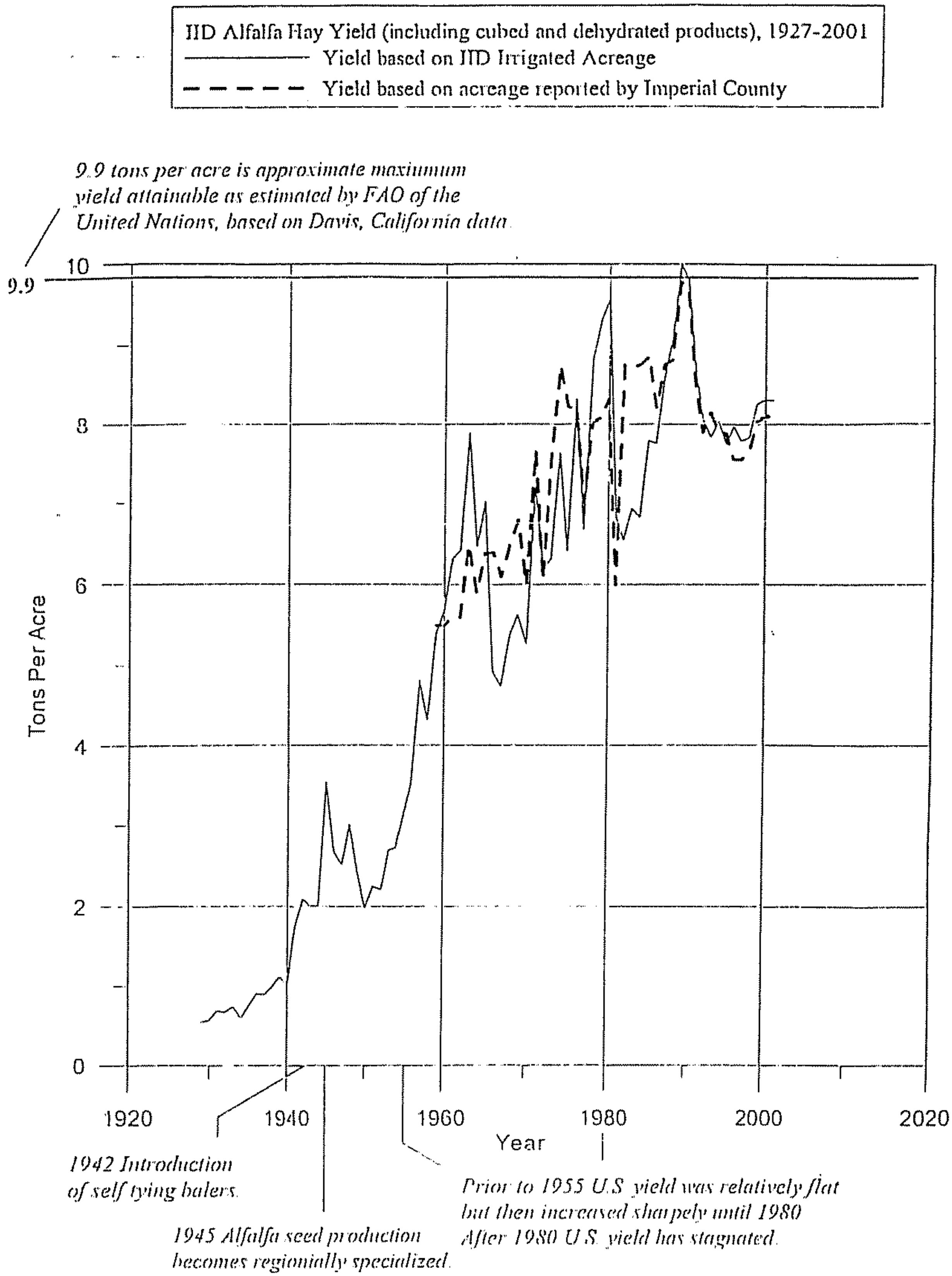
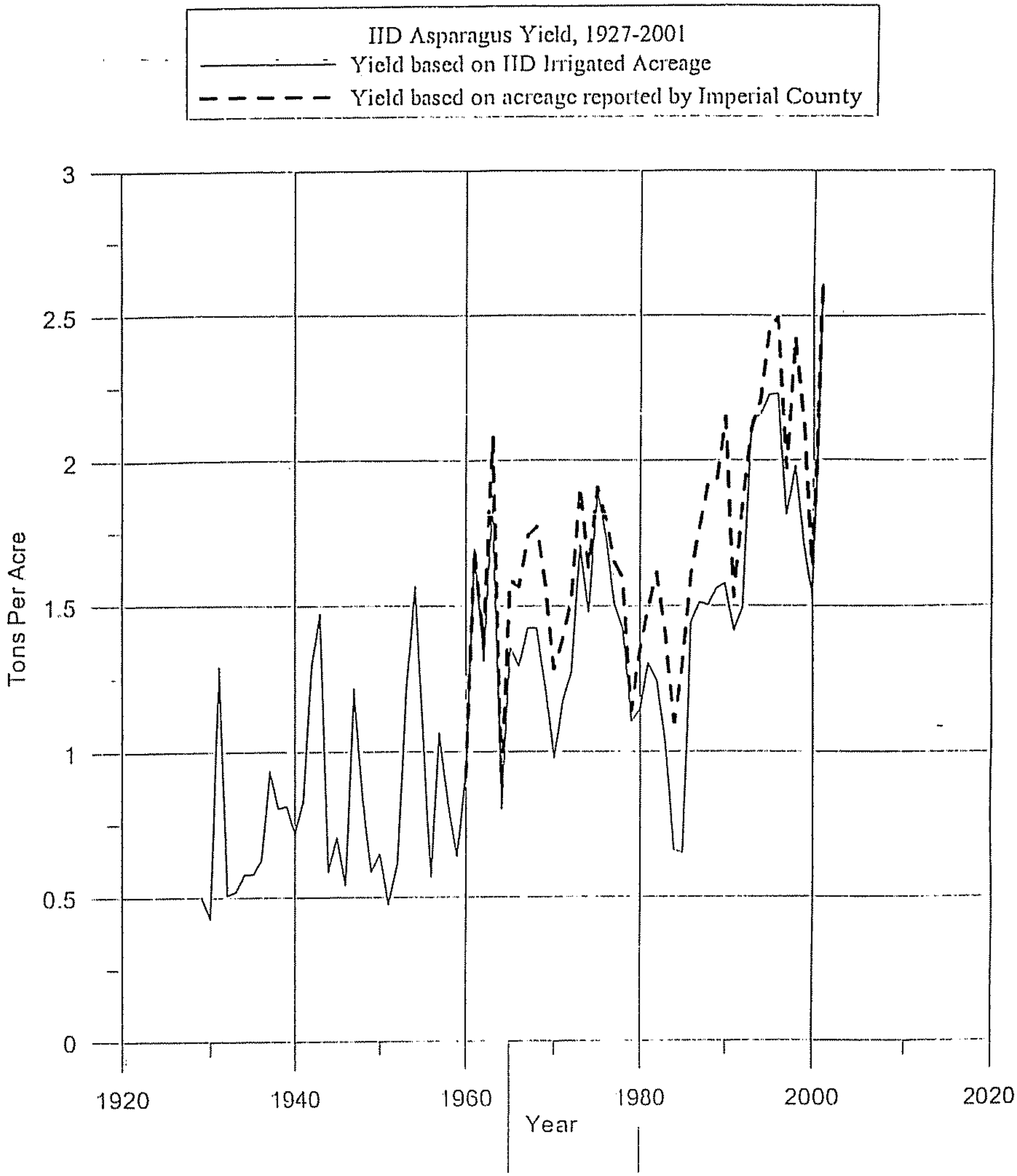
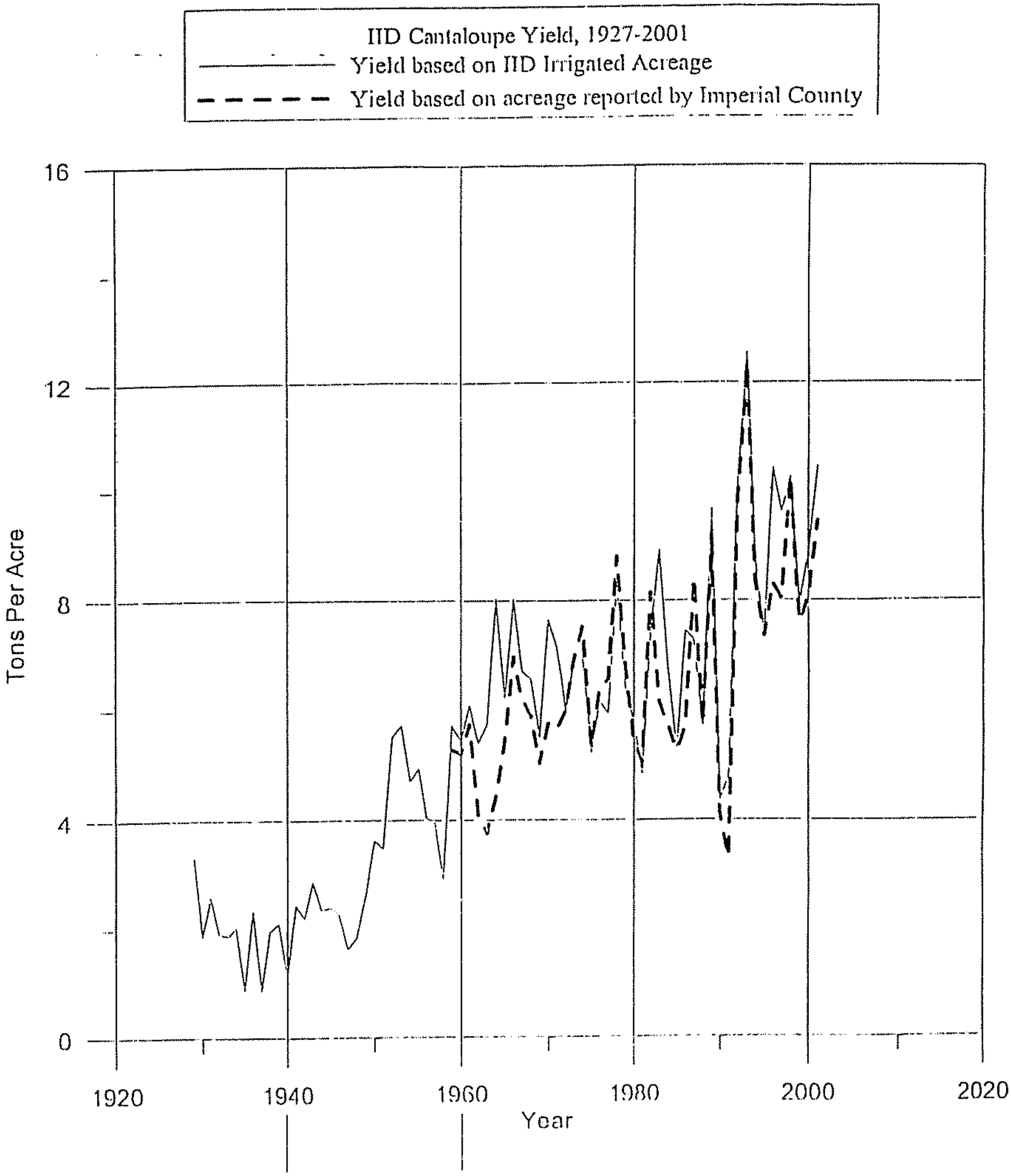

IID Alfalfa Hay Yield (including cubed and dehydrated products), 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
9.9 tons per acre is approximate maximum yield attainable as estimated by FAO of the United Nations, based on Davis, California data.
9.9
10
8
6
4
2
0
Tons Per Acre
1920
1940
1960
1980
2000
2020
Year
1942 Introduction of self tying balers.
1945 Alfalfa seed production becomes regionially specialized.
Prior to 1955 U.S. yield was relatively flat but then increased sharpely until 1980. After 1980 U.S. yield has stagnated.

Figure 1.



Statewide yields declined during period 1965-1980 due to Fusarium desease, labor and economic problems.

Figure 2.



Cantaloupe variety PMR 45's susceptabilaty to crown blight led to losses in IID yields during the 1940s and 50s and was replaced by the variety Topmark

Figure 3

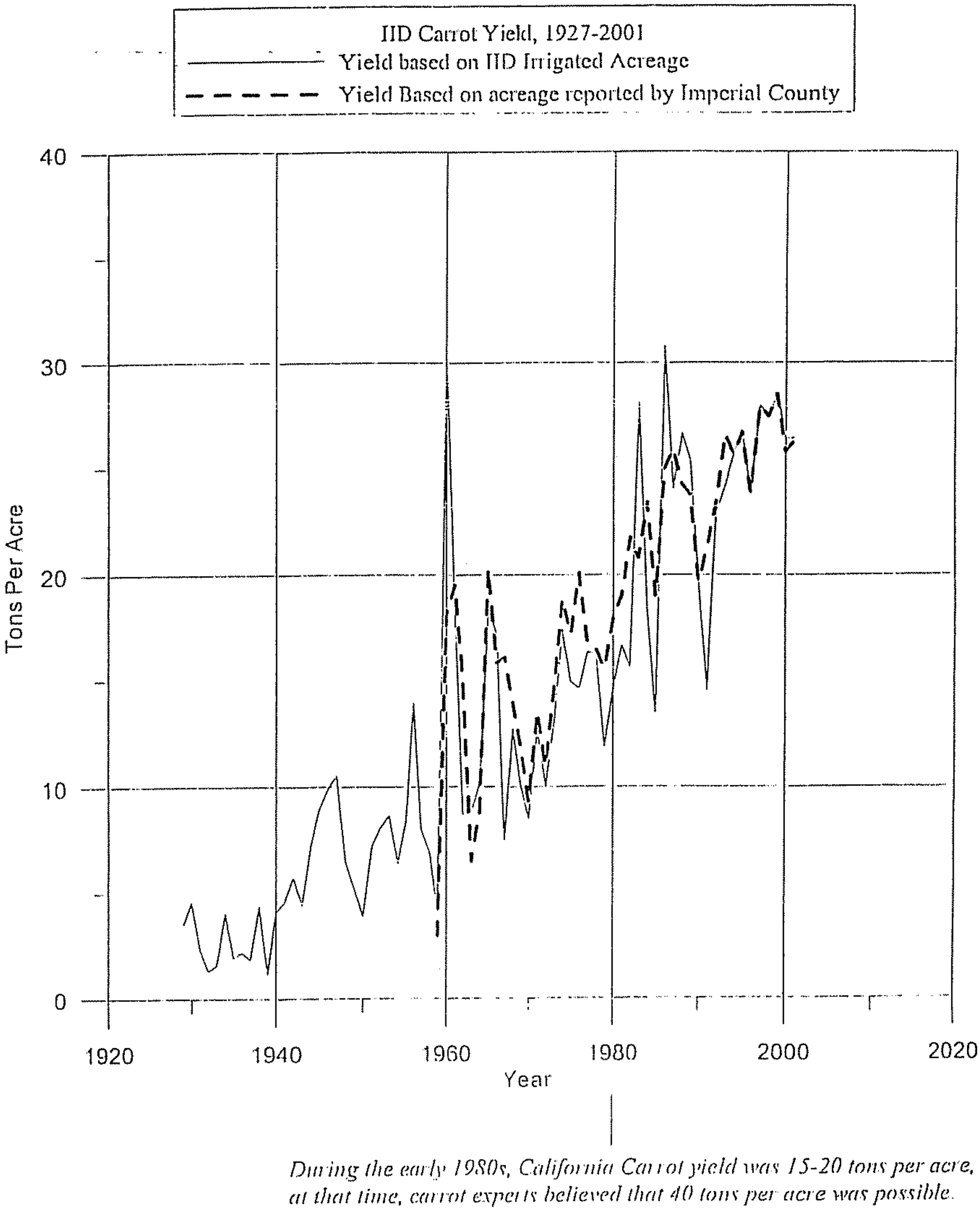

IID Carrot Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield Based on acreage reported by Imperial County
40
30
20
10
0
Tons Per Acre
1920
1940
1960
1980
2000
2020
Year
During the early 1980s, California Carrot yield was 15-20 tons per acre, at that time, carrot experts believed that 40 tons per acre was possible.

Figure 4.

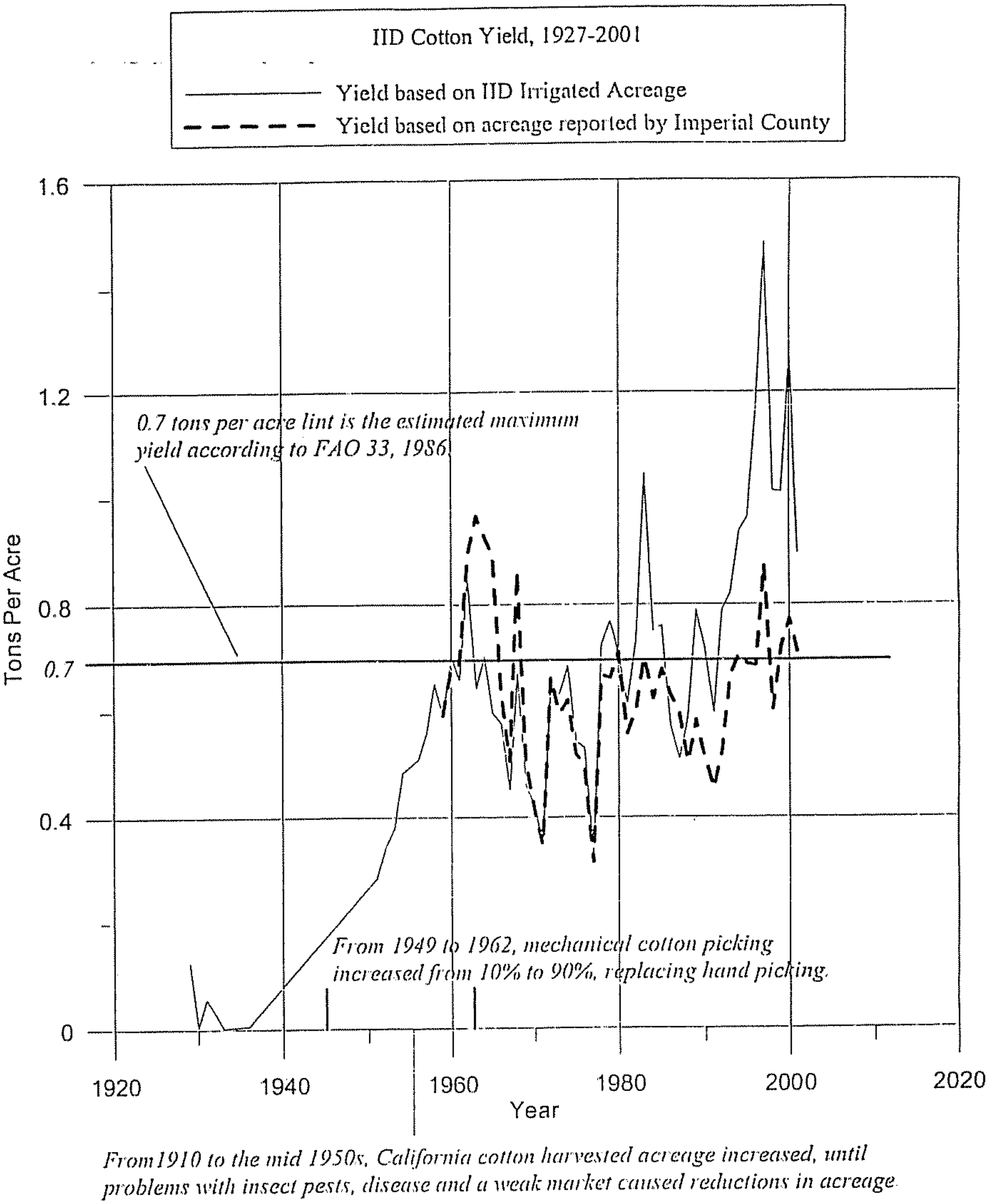

IID Cotton Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
1.6
1.2
0.8
0.7
0.4
0
Tons Per Acre
0.7 tons per acre lint is the estimated maximum yield according to FAO 33, 1986
From 1949 to 1962, mechanical cotton picking increased from 10% to 90%, replacing hand picking.
1920
1940
1960
1980
2000
2020
Year
From1910 to the mid 1950s, California cotton harvested acreage increased, until problems with insect pests, disease and a weak market caused reductions in acreage.

Figure 5.

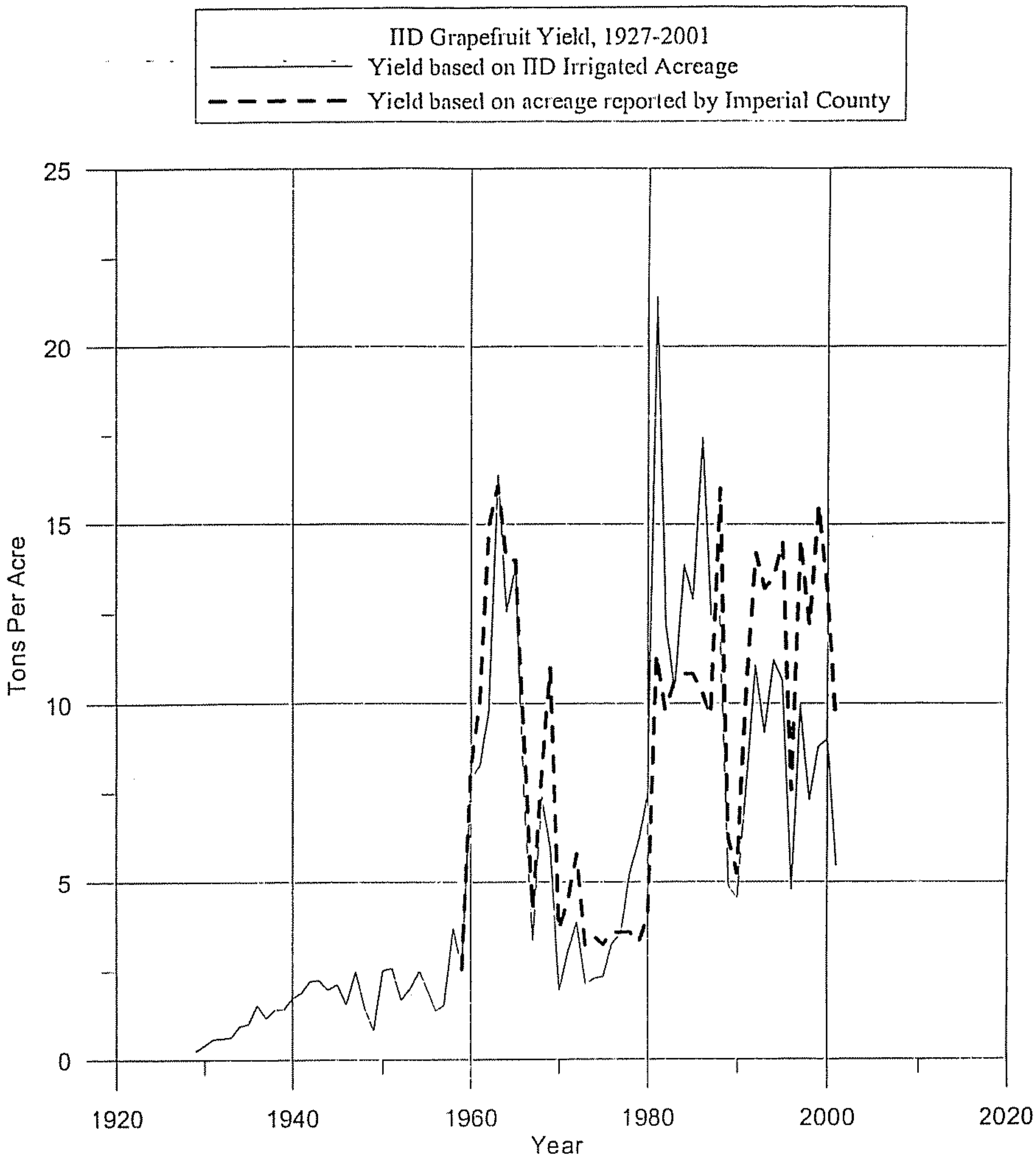

IID Grapefruit Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
25
20
15
10
5
0
Tons Per Acre
1920
1940
1960
1980
2000
2020
Year

Figure 6.

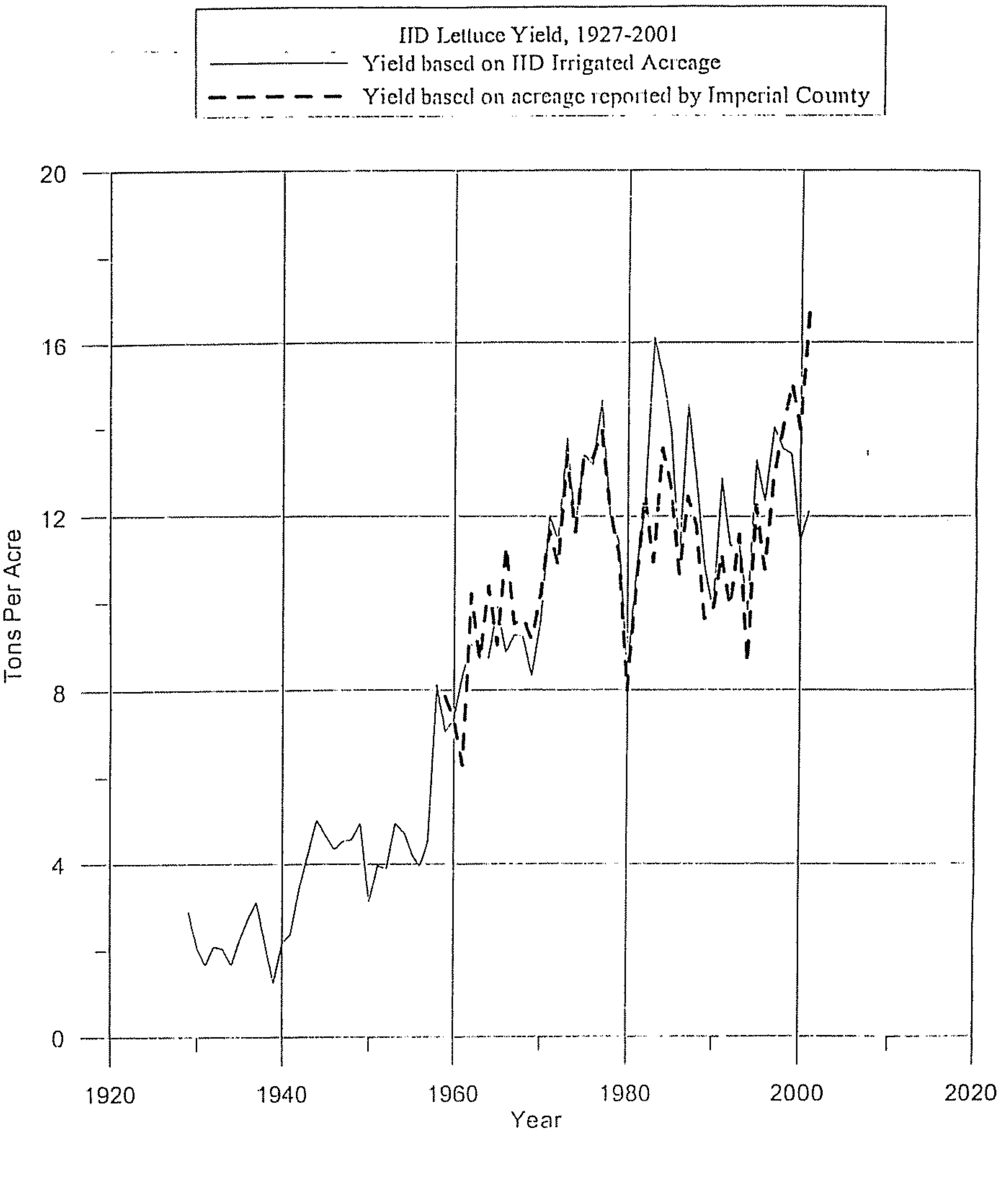

IID Lettuce Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
Tons Per Acre
Year
0
4
8
12
16
20
1920
1940
1960
1980
2000
2020

Figure 7.

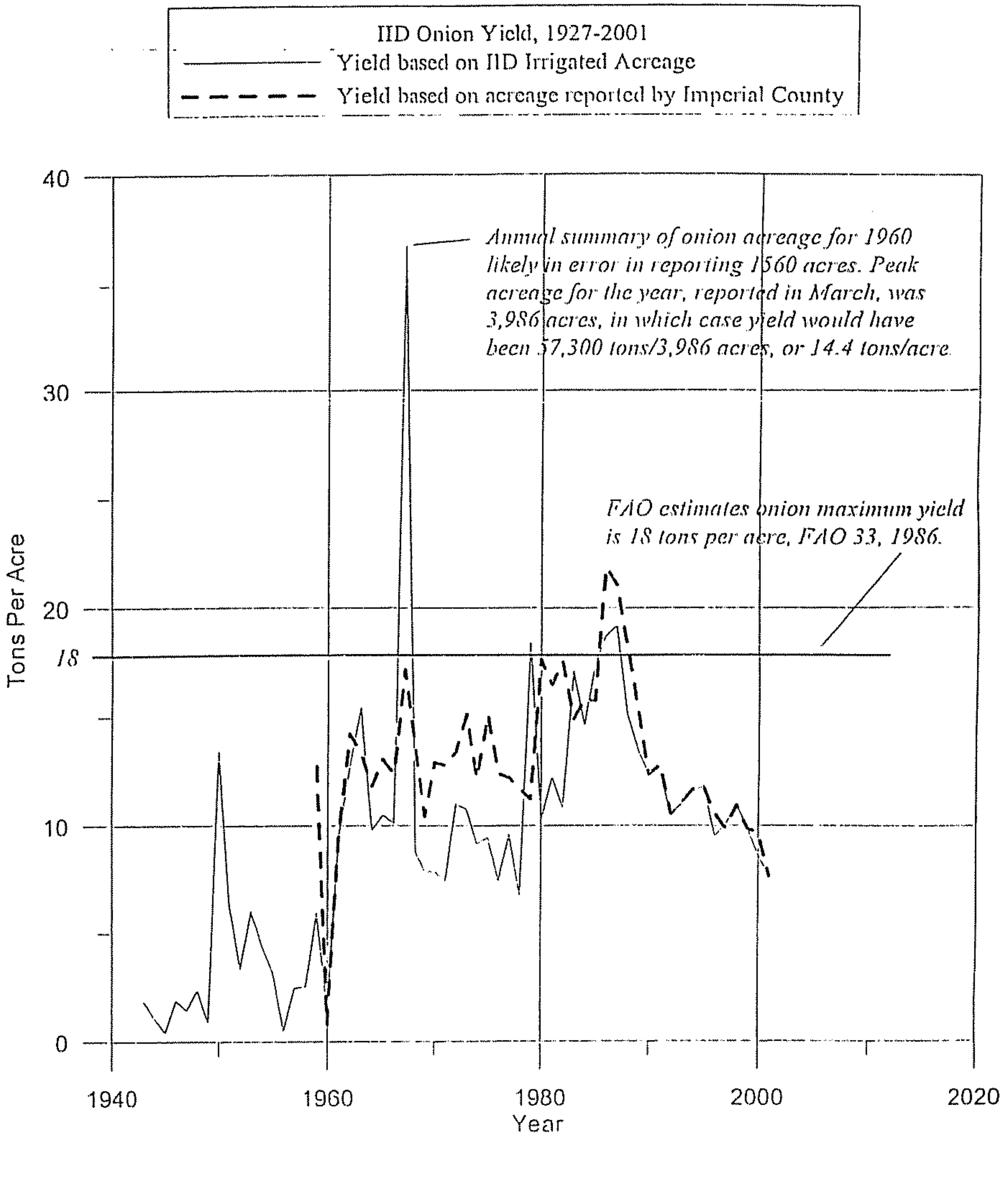

IID Onion Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
Annual summary of onion acreage for 1960 likely in error in reporting 1560 acres. Peak acreage for the year, reported in March, was 3,986 acres, in which case yield would have been 57,300 tons/3,986 acres, or 14.4 tons/acre.
FAO estimates onion maximum yield is 18 tons per acre, FAO 33, 1986.
Tons Per Acre
40
30
20
18
10
0
1940
1960
1980
2000
2020
Year

Figure 8

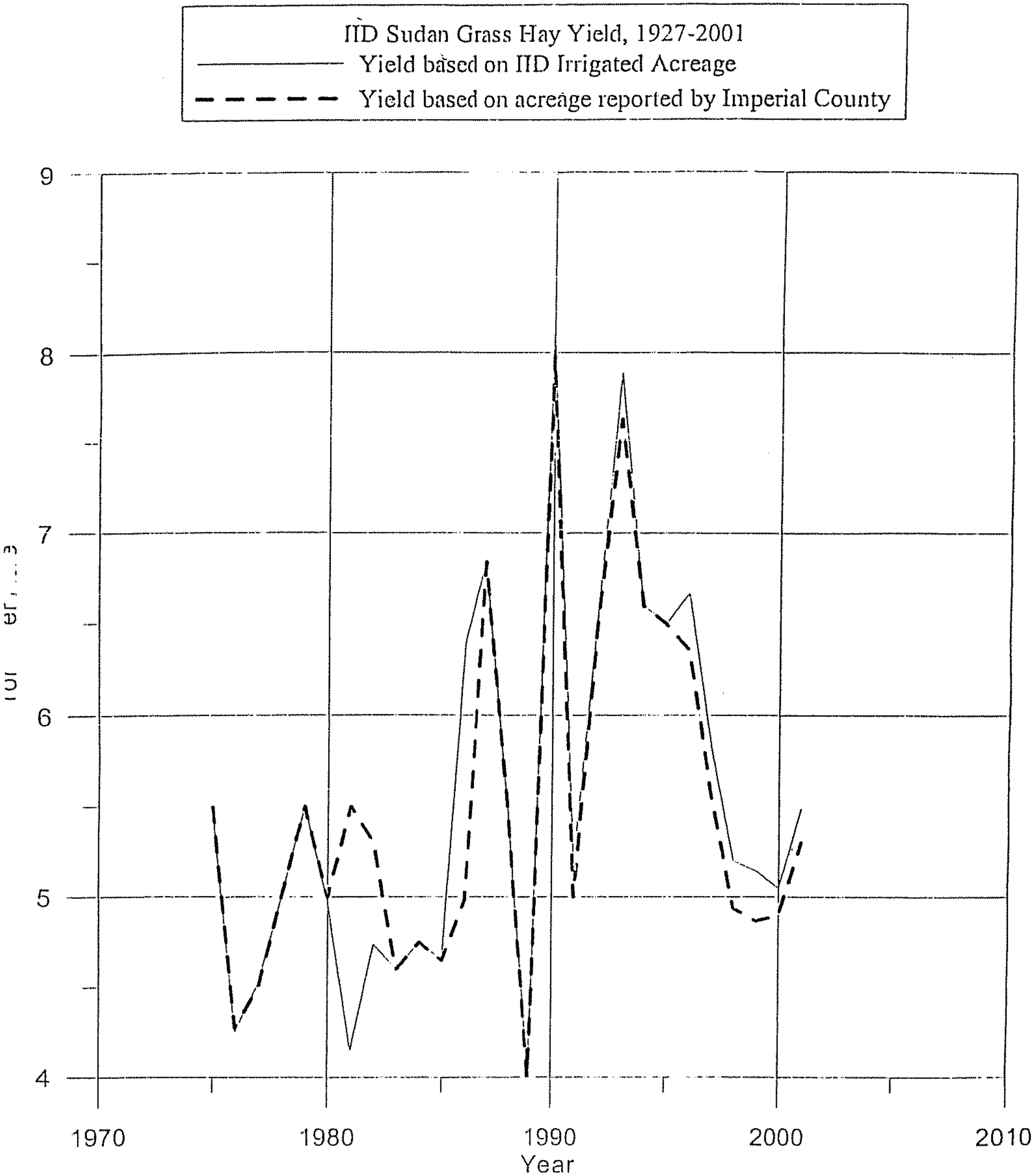

IID Sudan Grass Hay Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
9
8
7
6
5
4
1970
1980
1990
2000
2010
Year

Figure 9.

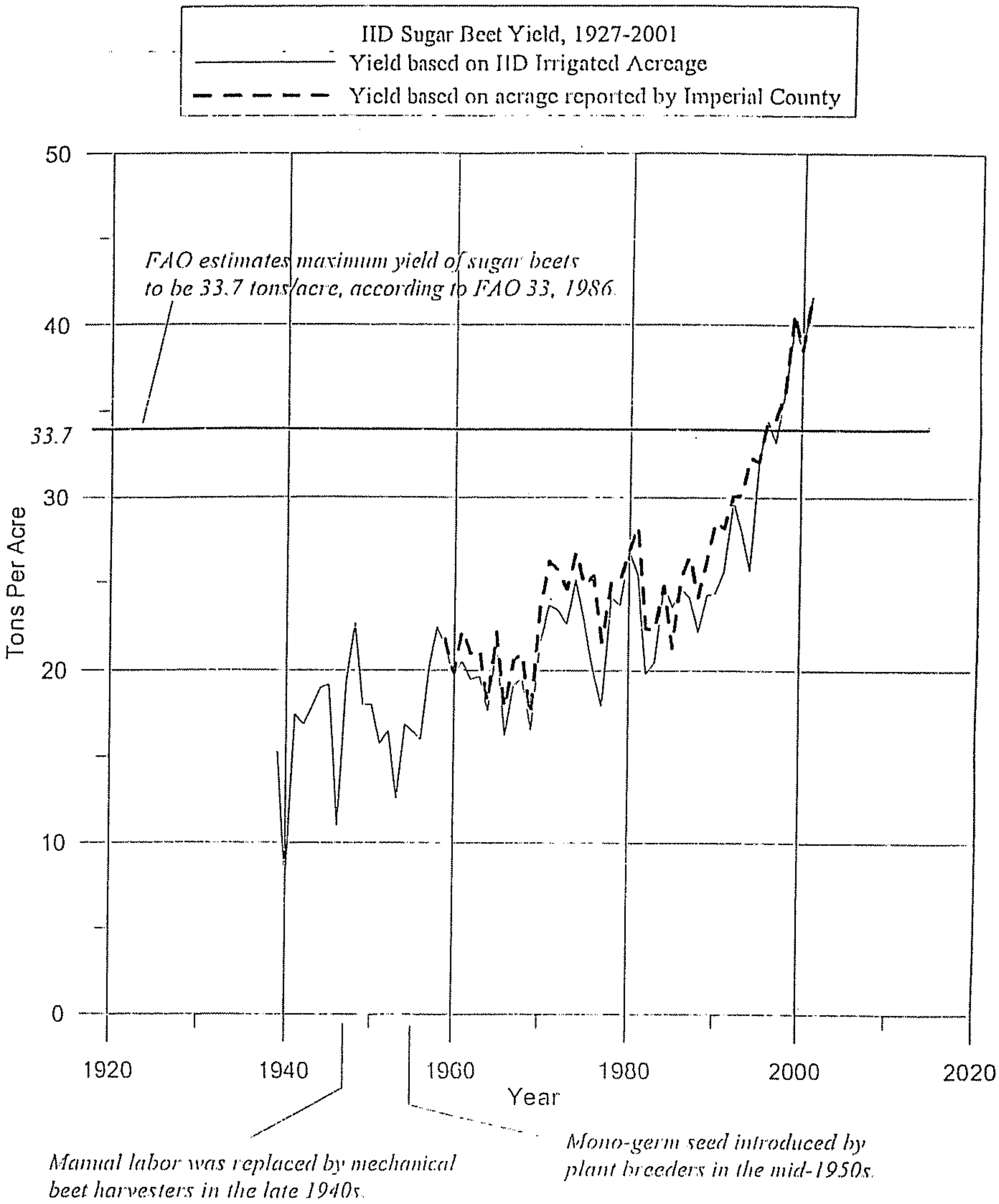

IID Sugar Beet Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acrage reported by Imperial County
FAO estimates maximum yield of sugar beets to be 33.7 tons/acre, according to FAO 33, 1986.
Tons Per Acre
50
40
33.7
30
20
10
0
1920
1940
1960
1980
2000
2020
Year
Manual labor was replaced by mechanical beet harvesters in the late 1940s.
Mono-germ seed introduced by plant breeders in the mid-1950s.

Figure 10.

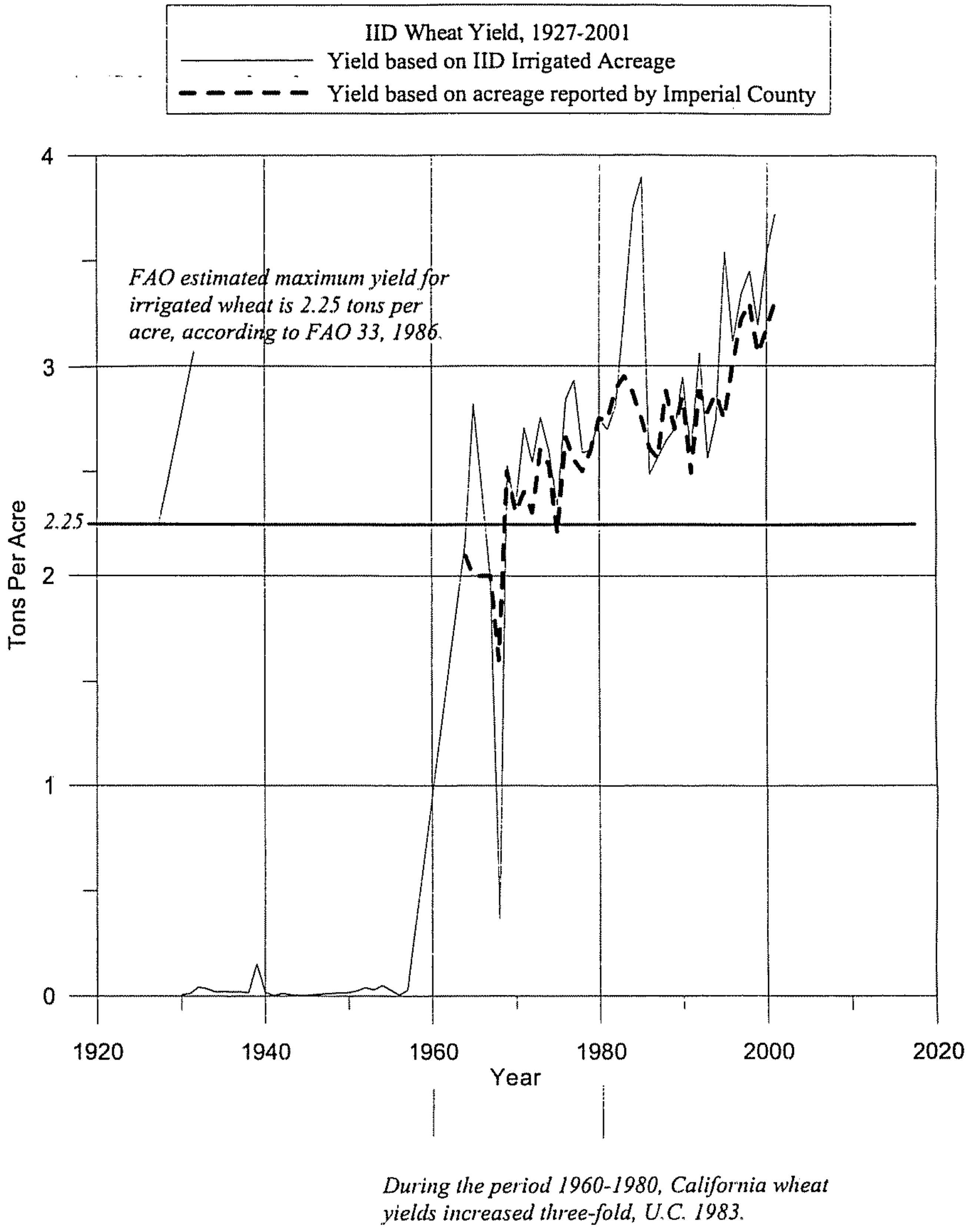

IID Wheat Yield, 1927-2001
Yield based on IID Irrigated Acreage
Yield based on acreage reported by Imperial County
FAO estimated maximum yield for irrigated wheat is 2.25 tons per acre, according to FAO 33, 1986.
4
3
2.25
2
1
0
Tons Per Acre
1920
1940
1960
1980
2000
2020
Year
During the period 1960-1980, California wheat yields increased three-fold, U.C. 1983.

Figure 11.

Field Crops:
Alfalfa, Cotton, Sudan Grass, Sugar Beets, Wheat

Garden Crops:
Carrots, Lettuce, Cantaloupes, Onions

Permanent Crops:
Asparagus, Grapefruit

Plots were generated for each of the remaining crops, each showing two yield curves. These yield curves were generated by dividing total annual crop tonnage by acreage figures from IID and acreage figures from the Imperial Valley Agricultural Commissioner's Office. Total annual crop tonnage was either reported directly or was determined by converting reported units into tonnage. Plotting data revealed an upward trend in per acre yield for all crops and occasional outlying points which appear not to match general trends. For each of the plots generated, data were rechecked for ordinates related to odd-outlying points. Outlying points appearing on plots were found to reflect data available and in most cases are believed to be the result of errors in crop and acreage data reporting. As can be seen from graphs, IID yields have risen dramatically over the period from 1927-2001. The implications of such large increases in yield cannot be overstated and it must be noted that such gains cannot logically occur without proportional inputs to the crops grown.

The reasons for increased yields are numerous, the combination of which have generated a more favorable environment for the crops grown. Various highlights in crop history are shown for some of the crops on the graphs. These include introduction of new machinery, new crop varieties and in the cases of intermittent declines in yield, notes regarding occurrence of specific diseases or pests. Review of papers by Wiersma (2001) and Putnam (1998) and discussions with Daniel Wiersma (now at Pioneer Seed), were used as a guide for the development of alfalfa and generation of alfalfa performance over period 1927-2001. It is important to note that general national alfalfa data yield records from USDA do not show the marked increases in yield as those associated with IID, because the USDA does not include the green chop and ensiled crop portion of the alfalfa yield (Wiersma 2003, personal communication). In discussing alfalfa yields, in general and with regard to IID, Wiersma indicated that the great increases in yield at IID are good and understandable based on climate and changes in technology and cultural practices.

The Crop Water Use and Yield Relationship

Food and Agricultural Organization of the United Nations

Generally, when considering crop water use and yield response, it is assumed that all factors are not limiting, except for water availability. This is a simplifying assumption which is useful in demonstrating the relationship between water use (evapotranspiration) and the formation of plant biomass. It is in this context in which most relationships between the water use of crops and their yields are identified. The most common use of this type of information is primarily focused on helping irrigators understand the relationship between crop yield reduction as a function of water shortage. That is to say, what yield can be expected from a crop which receives less than the optimal amount of water that could be used by the plant under perfect conditions of energy, water and nutrient availability, within an environment that is free from pests, disease, and other trauma. An assessment of crop yield response to water availability is presented in the FAO #33, 1986, a publication which is intended to generalize water use and yield relationships for various crops so that yield reductions can be anticipated, primarily for purposes of irrigation system planning and design world-wide.

The Wageningen method is one such method for estimating yield reductions on the basis of water shortage (from Slabbers 1978, within FOA #33, 1986). This method addresses alfalfa, maize, sorghum, and wheat crops specifically. The crop water/yield relationships for these crops was "calibrated and tested based on extensive experimental data covering a wide range of climatic conditions" (FAO #33, 1986). The model is found to be adequately useful in the determination of dry matter production for alfalfa, maize, sorghum, and wheat. "A further simplification of the linear model is given herein by assuming, amongst other assumptions, that maximum dry matter production occurs at maximum evapotranspiration, and by applying simplified corrections for dry matter production to obtain marketable yield" (FAO #33, 1986). Many crop water/yield relationships have been developed over the years by researchers and agronomists for purposes of addressing crop specific behavior within the context of regional environmental conditions. It can be said that while the rate of water use varies according to crops and environment, the basic relationship for field crops is linear, where yield is directly proportional up to a point approximately near maximum yield. At this point the "straight-line relationship" curves as the rate of yield increase decreases with increased water application. The basis for describing these relationships as linear is described in detail by various researchers. Some of this research and the conclusions drawn are summarized as follows according to authors Stanhill, Dewit, Arkely, and Stewart.

This approach is also useful in understanding the relationships between increases in yield and the water required for accomplishing greater yields. It should be pointed out that the yield of a given crop at a given location, is an expression of the integration of all factors which give rise to the harvestable portion of the crop plant; therefore, generalized crop water use and crop yield functions are not necessarily transferable from location to location. In spite of this, it is correct to say that crop yields will increase proportionately with increased water availability, up to a point determined by the crops ability to produce biomass, where biomass production is governed by the environment and the plant's ability to convert energy from the sun into energy used by the plant to carry out its physiological processes.

Stanhill

Stanhill discussed water use and crop production in the following manner: "An important scientific problem in connection with commercial irrigation practice concerns the effect of varying soil-moisture deficits on crop growth. Since Veihmeyer's classical work showing it impossible to maintain a constant soil-moisture status around the roots of a transpiring crop, the problem has been interpreted in terms of degree of depletion of available soil moisture that can be tolerated by a crop without adverse affect on yield" (Stanhill, 1956).

In his studies, Stanhill reviewed previous scientific literature to determine previous studies which defined the soil moisture regime in a consistent manner, that being: "For purposes of this paper a soil-moisture regime is defined as an irrigation treatment in which the soil is allowed to dry until a definite measured point is reached within the available water range before sufficient water is applied to restore the entire root zone to field capacity."

Field capacity can be described as the level of water retained by the soil after all gravimetric water, or water drained by gravity, has flowed out of the soil. Different soils have different field capacities, much like different sponges might have varying degrees of water holding ability.

Stanhill found: "Of the 80 papers describing investigation where the above definition of soil moisture regime was satisfied the results of 66 showed that plant growth did respond to differences in soil moisture regime and the results of 14 showed no such significant response. In all positive results, with the exception of a carrot seed crop, greatest yields were associated with the wettest regimes." Furthermore, "The greater likelihood of positive response to variations in available soil moisture found with annual plants, is probably connected with the fact that many annual crop plants are grown for their vegetative tissue, while most perennial plants are grown for their reproductive organs. The smaller proportion of positive results from experiments where reproductive growth was measured can be associated with the ability of reproductive parts of the plant to compete successfully with vegetative tissue for limited water supplies during periods of water stress." The most dramatic examples of increased plant biomass in crop production, as a function of water consumed by the plant is therefore most evident in crops where most of the plant is harvested.

De Wit

One of the early, comprehensive studies of crop water use and production relationships was conducted by De Wit, the results of which were published in 1958 in a document entitled *Transpiration and Crop Yields*. This study addresses two cases of relationships which define water use and crop yield. De Wit describes these as: "At present it is generally accepted that transpiration of field crops is limited by either (a) the supply of water to be evaporated or (b) a supply of energy to provide the heat of vaporization of the water. The extreme of high energy supply and low water supply introduces great difficulties in a completely physical approach. At the other extreme of plentiful water it is possible to apply known physical principles which lead to the concept of "potential transpiration". This is the rate of evaporation from an extended surface of a short green crop, actively growing, completely shading the soil and never short of water." Clearly IID falls within the first category, as sunlight is not limiting and water availability is. Some of De Wit's findings are summarized below:

"It is shown in this paper that the relation between transpiration and total dry matter production of plants in containers is much less affected by growing conditions than supposed. In the semi-arid and arid regions of the U.S.A. this relation appears to depend mainly on plant species and free water evaporation. In cloudy regions as found in the Netherlands it depends mainly on plant species, only. The effect of factors like soil fertility and availability of water appears to be of secondary importance, except in extreme conditions."

"It is shown that the relation between transpiration and total dry matter production of plants under field conditions must be often the same as for plants in containers provided the dry matter production of the plants in the field is limited by the availability of water. Where this latter is not the case, transpiration tends to be higher. Difficulties were met in dealing with the interrelation between drought resistance and transpiration-production relations and with the contribution of advective energy to transpiration. As for drought resistance, it is shown that the relation between transpiration and total dry matter production is not affected by the ability of the plant to withstand periods of drought. Instead, the amount of marketable products and the total amount of water which is transpired during the growing period, may depend to a large extent on this ability."

De Wit compared results from various crop water use and yield experiments that show the basic relationship between water use and crop yield. De Wit considered the results from experiments conducted by others, some of which are presented below for examples of dry arid climates. See Figures 12 and 13 from De Wit. Figure 12 shows graphical representations of crop yield versus water use for three different crops grown in containers at various arid sites. The vertical (y) axis is the ratio of the weights of water and dry matter associated with the harvested portions of the plants. The horizontal (x) axis represents water consumed in terms of millimeters per day. The form of the function is interpreted as being a straight line or positive linear function between biomass and water consumption. Figure 13 shows the results of seven crop field trials conducted during the early 1900s. The y axis of these graphs expresses alfalfa yields in tons per acre, while the x axis represents water consumption, expressed in millimeters per day. In all cases, both container and field grown crops show the same behavior in that yields increase with water consumption.

Arkley, 1962

Arkley conducted research regarding transferability of relationships of water use and yield by addressing factors affecting crop water use in relation to yields for oats, barley, corn, sorghum, peas, alfalfa, and wheat, which was published in the Journal Hilgardia in 1962. Arkely researched previously defined water use and yield relationships and addressed environmental factors such as atmospheric humidity, differences in plant species, availability of water, and the effect of soil fertility. Arkley states: "Although most of the water transpired by plants is considered nonessential to the process of plant growth (formation of actual plant tissues as opposed to water transpired), transpiration and growth tend to increase together because, obviously, evaporative demands on a plant must be met if the health and vigor of the plant are to be maintained. As Kramer (1959) pointed out, 'failure to replace water lost by transpiration results in loss of turgidity,

Figure 12.

Relationships Between Transpiration Ratio and Evaporation from Evaporation Pans as a Measure of Dry Matter Yield and Crop Transpiration, for Sorghum, Wheat and Alfalfa De Wit (1958).

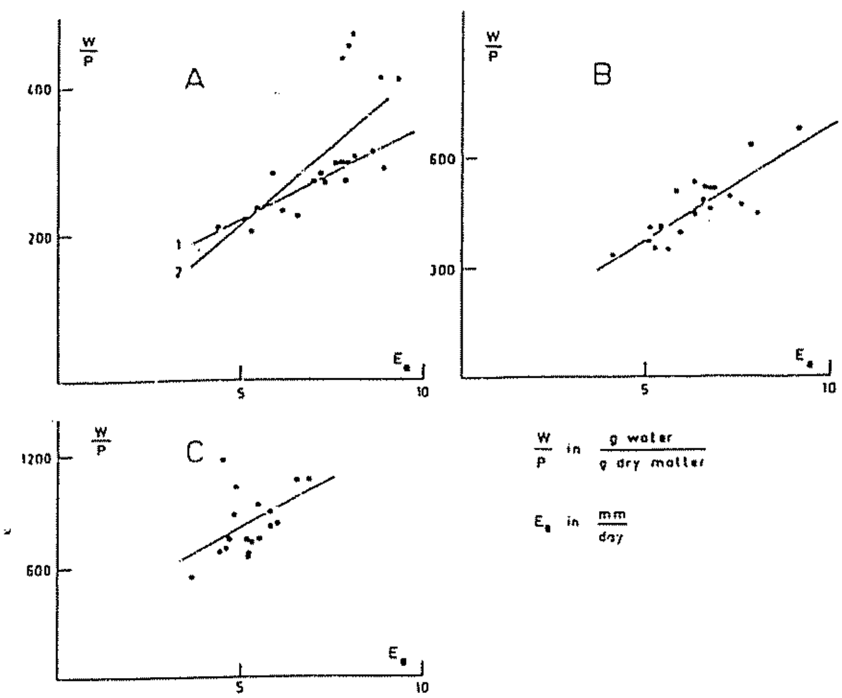


FIG. 22. Diagrams showing the relation between the transpiration ratio – WP^{-1} – and the evaporation from an evaporation pan – E_t – in different years in Delhart (Texas), Akron (Colo.), Mandan (N.D.), Newell (S.D.) in U.S.A. (circles) and in Bombay in India (dots).
The data are obtained from table 6.
Graph A: sorghum; B: Kubanka wheat; C: alfalfa
The lines represent the regression equations of table 7. Line 1 in figure A holds for the data in U.S.A. and line 2 for the data in U.S.A. and India, both.

Figure 13.

Relationships Between Alfalfa Hay Yield (dry matter production) and Water Use in Millimeters per Day for Six Locations De Wit (1958).

65

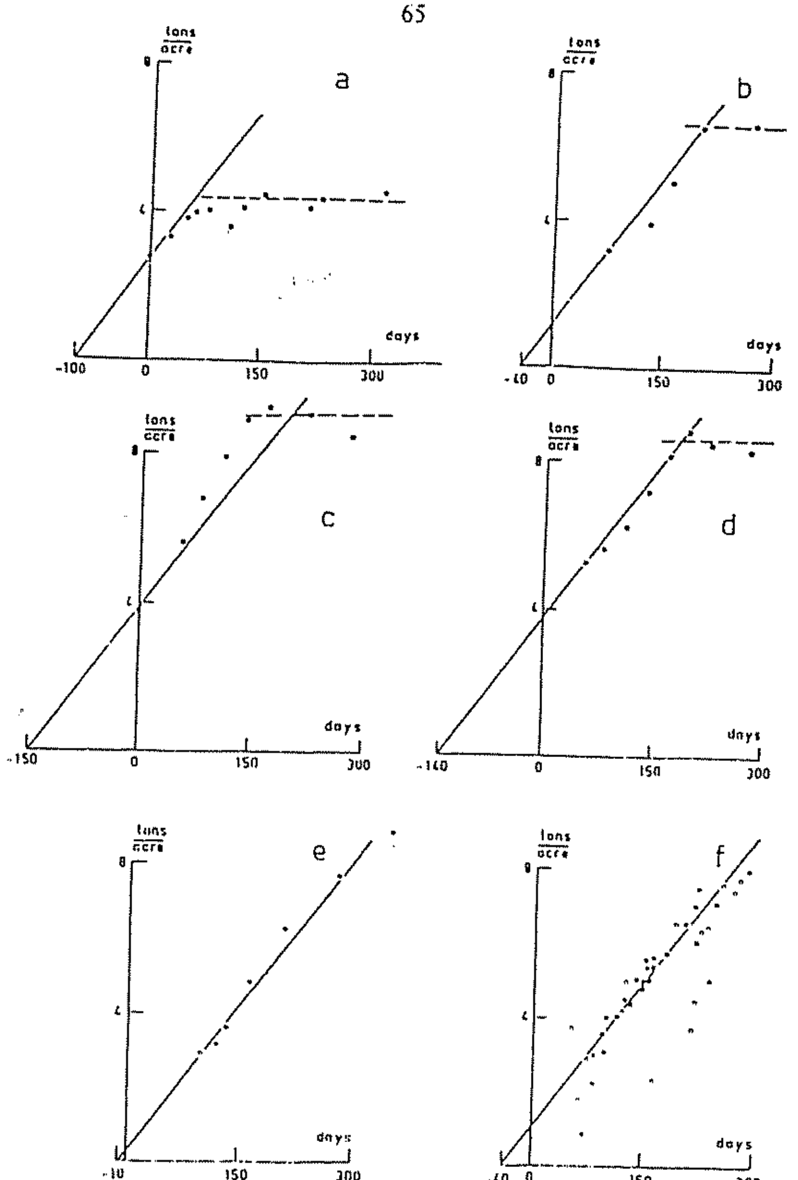


FIG. 37 The relation between hay yield in tons per acre and applied amount of water in days. The points are observed values. The slope of the line through the observations at the lowest application is in all cases 0.026 tons $acre^{-1}$ day^{-1} and obtained from the pot experiments of figure 24

	E_o (mm day^{-1})
a. Experiment in Logan (Utah)	4.5
b. ,, ,, Gooding (Idaho)	4.0
c. ,, ,, Davis (Cal.)	5.5
d. ,, ,, Delhi (Cal.)	5.5
e. ,, ,, Highley (Ariz.)	6.0
f. Experimental results on farmers' fields in Salt River valley (Ariz.)	6.0

E_o values are rough estimates of seasonal evaporation of a free water surface.
For sources and details see text.

cessation of growth, and eventual death from dehydration.' Graphs were plotted from data of earlier workers; Hellriegel (1883) and Schroeder (1886) for barley, Fortier (1903) fro oats, and Wimmer (1908) for carrots. In every case the graphs showed a linear relationship between the amount of dry matter produced (Y) and the amount of water transpired (Tr) by a particular species of plant under given conditions of climate and soil fertility." Arkley proposed the equation $Y = k\ TR$ to describe the relationship of yield to transpiration for a given climate and fertility. The regression coefficient or proportionality constant, k, is the parameter that depends on the kind of plant and is the reciprocal of the transpiration ratio. Arkley found that: "A correction for climate based on mean monthly relative atmospheric humidity makes it possible to combine the data on yield and transpiration from different years and different localities with correlation coefficients of greater than 0.95. This amount of correlation ($r^2 = 0.90$) accounts for about 90 percent of the variation among different experiments, provided that soil fertility is controlled at a constant level. The data available for determining a correction based on differences in soil fertility are less reliable than those used for the humidity correction." Arkley concluded that: "it seems evident that quantitative expressions for the relationship between plant growth and transpiration and for the effect thereon of changing soil or environmental conditions should be significant in any study concerned with the use of water by plants."

Stewart et al., 1973

Stewart's work was focused on the development of predictive methods regarding crop water use and yield, specifically for purposes of aiding planning for the allocation and use of irrigation water. As with Arkley's efforts, Stewart found that: "The functional relations between crop yield and water now available are either assumed or derived from empirical experimental findings under limited conditions." "These functions, typical of others indicating that yield initial rises to a maximum and then falls with increases in seasonal depth of applied irrigation, were used by Clyde, et al. to illustrate that net profit is maximized at some irrigation level associated with maximum yield. The precise level depends on the quantitative response of yield to water deficits, and on the relative prices of harvested crop and water." Significant to the purpose of showing the relationship between water consumption and yield are Stewart's comments regarding the nature of the relationship.

"The striking linearity of the Y versus ET function, which is a virtual duplicate of the function found in 1970 (an earlier study), leads directly to the question of whether a fundamental relationship is expressed. Certainly these findings support a considerable body of earlier work indicating that Y versus ET functions of many crops may be linear. This point deserves a short analysis, because a finding in favor of basic linearity holds tremendously important implications for prediction of water-production functions of all types."

Stewart's paper goes on to develop in detail the variations of yield vs. evapotranspiration (unlike previous investigations which focused only on transpiration) and further identifies the difference between past treatment of yield, which represents total dry matter produced and true harvested yield. So, in addition to addressing the evaporation component of evapotranspiration, he also addresses details such as differences in relationships based on growth (G) (the standard used in past studies) as opposed to true yield, which he discusses in terms of the yield of harvested portions of crop plants. Stewart states: "Many early researchers grew plants of normal size in fertile soil in large covered containers under field conditions, and measured primarily transpiration (T) and growth (G), I.e., total production of dry matter. For the most part the containers were well watered to study the "water requirement" or transpiration ration" (T/G), which differs greatly between species, somewhat with variety, and considerably with climate. However, several noteworthy studies of effects of T deficits on G were also carried out. Briggs and Shantz reported such a study with wheat, Miller and Duley with corn, Kiesselbach with corn and grain sorghum, and Dillman with oats. When the findings are plotted with G as a function of T, the result in each case is a straight line which passes through the origin."

Stewart describes the differences between growth (G) indexed functions with actual yield functions (Y). In his analysis he addresses differences between field conditions and differences in perennial and annual crops and states the following in this regard:

"Before considering whether the Y function should be linear like the G function, it should be pointed out that the E (evapotranspiration), in a full cover crop such as alfalfa, behaves differently from that in annual crops which have an early-season crop-stand establishment period. It is the early-season E which displaces the G versus ET function of annual from the origin. That this is not applicable to full-cover forage crops is illustrated by findings of Scofield who grew alfalfa in large open containers with three watering programs. When plotted, the G versus ET function is linear and through the origin. The inference is that E under full-cover crop conditions is always a somewhat constant percentage of ET and therefore probably reduces the slope of the linear function but does not displace the function from the origin. On the other point concerning forage crops: Y and G are often synonymous, sot that the G versus ET and Y versus ET function are one and the same."

"Whether the Y versus ET functions of grain crops remain linear will depend on the nature of changes in the ratio Y/G with increasing ET deficits. In terms of mathematics it is clear that if this ratio remains constant, the function is linear. It is perhaps less clear, though fully as true, that if this ratio either increases or decreases in any steady fashion with increasing seasonal ET deficit, the function will also be linear."

Estimation of Past Crop Water Requirements Using FAO Yield Response to Water

Approximations of past water use by various crops were made using generalized water use and yield relationships presented in FAO publication #33. This was conducted for purposes of demonstrating the reduced crop water requirements of these crops, as would be expected to have occurred in the past, when growing environments were less than optimal. The crops addressed include: alfalfa, cotton, citrus, onions, sugar beets and wheat because specific crop yield response factors (ky) were developed by FAO for these crops. The analysis is based on the historical yield data based on Imperial Irrigation

District's acreage and yield records, as presented in the previous graphs, corresponding to these six crops.

The following are important points regarding the treatment data and interpretation of results for this purpose:

1. FAO relationships are generalized for many growing conditions and are intended as guidelines for purposes of estimation of yield reductions as a result of water deficit.
2. The crops addressed by FAO include only six of the crops identified by NRCE as major crops grown in IID.
3. These approximations are not absolute, since the relationships developed by FAO are intended for use within certain limits of the water/yield response relationship. Specifically, that water use as a function of yield is linear and valid for water deficits up to 50% of yield. Deficits greater than 50% are not addressed directly by FAO, as other factors may be significant within this range of yield reduction.
4. For purposes of this analysis, the relationship is assumed to be indicative of lower yields and since the range of yield is so great regarding the cropping history of IID, it is acknowledged that other factors may have affected yield, other than water. This is particularly true of the earliest part of cropping history, during which time irrigation and cropping practices were likely in the process of rapid development and therefore had not been stable. For example, problems with irrigation water distribution were more significant in the early years and as well, efficiency of harvests were relatively low. Low harvest yield in the early years understates actual crop yield since a good portion of the crop irrigated and grown may not have been reported. In such cases, complete yields were not harvested due to difficulties in field operations. This is due to crude harvest technology and difficulties associated with getting crops to market. During such times in early crop history, the farmer was less likely to harvest if crop prices paid to farmers were anticipated to be low. Harvest costs often represent the major portion of crop production. Because of this and the uncertainty associated with early crop statistics, the use of the early harvest yield data were omitted for purposes of estimating crop water use in this analysis.
5. In this analysis, estimates of actual, historical water use by crops are stated as a percentage of the water required by today's crops producing at near maximum yield. This is accomplished by using the relationship between relative yield decrease (1-Ya/Ym) and relative evapotranspiration (1-(ETa/ETm), as related by the yield response factor ky, as defined by FAO for each of the six crops identified above.
6. Table 1 shows the time period considered for each of the crops, the increase in yield over this period, the ten year average past and recent historical yields, the FAO yield response factor (ky) and the estimated past water consumption of the six crops, as a percentage of water required by those crops as recently grown.

Table 1. Estimated Difference in Present and Historical Crop Evapotranspiration							
Crop	Period	Initial 10 yr. avg. period	Recent 10 yr. ave. period	Yield Increase Factor X	FAO (ky) total grow period	Relative Yield Reduction 1-Ya/Ym	Relative ET Deficit 1-ETa/ETm
Alfalfa	1942-2001	2.46	8.02	3.26	1.1	0.69	0.63
Cotton	1952-2001	0.54	1.04	1.91	0.85	0.48	0.56
Citrus	1942-2001	1.99	8.73	4.38	1.1	0.77	0.70
Onions	1943-2001	3.30	10.17	3.08	1.1	0.68	0.61
Sugar beets	1942-2001	17.77	33.95	1.91	1	0.48	0.48
Wheat	1964-2001	2.46	3.23	1.31	1.15	0.24	0.21

Though the results are not absolute, it can be seen from this analysis that crops in the past used less water than those presently cultivated within IID. Table 1 shows that alfalfa, cotton, citrus, onion, and sugar beet yields increased by three-fold, two-fold, four-fold, three-fold, and two fold, respectively, from the 1940s to the 1990s. Wheat yields increased by 30% from the 1960s to the 1990s.

Table 1 shows that the estimated crop evapotranspiration of alfalfa, cotton, citrus, onions, and sugar beets should have been 63, 56, 70, 61, and 48% lower, respectively, in the 1940s compared to the 1990s. Estimated evapotranspiration of wheat should have been 21% lower in the 1960s compared to the 1990s.

Summary

Water use by the crop plants grown within IID has increased over time by virtue of increased biomass production. It is therefore incorrect to say that present water use, by a given type of crop plant is the same as in the past. The USBR purports to have determined water use by IID for present and past years. Several things may have happened here. One is that the USBR has assumed a constant set of conditions have prevailed in IID over the years. In so doing, the USBR has estimated ET of the district incorrectly. Specifically, the change in yield, as shown by plotting yield data, indicate that crop ET would have changed (increased) over time as crops increase production. Based on yield response relationships, such as those previously presented, it can be said that yield varies directly with ET, up to the point of maximum yield. If this is accepted, then it can be said that water use, from 1927 to 2001 has increased as yield has increased, with regard to water consumed by the plant, though water diversion by IID has remained relatively constant.

Several possible cases exist with regard to the various crops grown. First, some crops were underperforming and producing far less than maximum yields. In this case, yields have increased and will continue to increase to the maximum yield possible under the conditions prevailing. This includes economic constraints which determine the point on the crop producers production function which define the beginning of diminishing returns. Therefore, producers will not seek maximum yields but something less, which represents optimal production levels that reflect the best return on their investments. The second thing to consider is that the traditionally held view of maximum yields for certain crops has been exceeded in some cases. In such cases, it can be said that for these crops, ET maximum, or the ET associated with maximum yield, was also incorrect. Based on this, it can be said that for crops which have yet to reach the level of maximum yield, estimates of ET for past crops have been overstated. The degree of over-estimation would increase, going back in time (as yield decreases). For crops which have exceeded commonly held limits to maximum yield, it can be said that present-day estimates of ET may be underestimating potential ET.

FAO 33 depicts yield response based on a static set of conditions. These conditions define the change in yield as a result of varying water availability based on estimated maximum yield of a given crop. These conditions are similar or are the same as those which define crop evapotranspiration. It seems the USBR has compared past and present water use on the basis of ET_c, which assumes that water requirements past and present are the same for a given set of crops. In reality, the amount of water used by crops in the past must have been less than the ET_c presently calculated for historical conditions since past conditions obviously produced substantially lower yields.

The lower yields of early years may have been the result of water deficit at the crop level caused by poor distribution of irrigation water. However, other factors no doubt played a major role in reducing past yields. These factors include lack of fertilizer, pests, poorly suited crop varieties, underdeveloped cultural practices, less than optimal plant density, fewer harvest cycles and lower efficiency of harvest. Factors which reduced yield, excluding harvest efficiency would have produced two results. One is lower water efficiency of crops, in that crops were growing under less than optimal conditions and were therefore not using applied water efficiently (lower dry matter production per unit water). Secondly, and just as likely, crop fields were not using as much water as they would if they had been producing near maximum yields. Related to this is the possibility that maximum yields for various crops have changed over time.

If one assumes that crop/yield relationships and maximum yield have been constant, it seems that most crops presently grown in IID are presently approaching optimum yields, somewhat less than maximum yields. If this is so, then past low yields were a result of less than optimal conditions and therefore, it would be an error to apply standard kc values when calculating past water requirements. Furthermore, if project water supply has remained constant, then past crops were over irrigated and/or overall efficiency, including crop water efficiency were substantially lower. The present state of water consumption within the project reflects a trend toward near maximum yields as far as maximum yields are understood. Calculated water requirements for present crops are therefore closer to the textbook conditions. Water requirements of crops over the history of the project cannot therefore have been the same over time, if maximum yield occurs at maximum transpiration.

Conclusions

Water diversion by IID has remained relatively constant over the years, as have irrigated acres, yet yields of crops have increased dramatically since the early years. Based on the foregoing literature review regarding the relationship between water consumption and yield, it can be seen that crop yields vary proportionately with water supply (water available to the crop), subject to environment, crop type, and general vigor. Furthermore, improvements in technology and farming practices over the years have in fact produced a more favorable environment for crop growth. Based on this, it can be said that agricultural operations of IID are more efficient than in the past at supplying water and providing favorable environments for crops. It should be clear that water conveyance, delivery, and application to farms has thereby increased in efficiency and that farming operations as a whole are more effective and efficient than in the past. It is evident that crops presently grown within IID consume more water than in the past because growing conditions of the past were far more limiting. Through the years, conditions which limited water consumption have been eliminated or partially eliminated, thereby allowing crops to grow and increase biomass production up to or near estimated maximum limits. Since the total amount of water diverted by IID has remained relatively constant, it follows that the additional water input necessary to allow for the visible increases in production has come from improvements in water conveyance, distribution, and application within IID. It is in this manner in which the additional water, required by more vigorous crops is made available

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Figure 12.

Relationships Between Transpiration Ratio and Evaporation from Evaporation Pans as a Measure of Dry Matter Yield and Crop Transpiration, for Sorghum, Wheat and Alfalfa De Wit (1958).

Figure 13.

Relationships Between Alfalfa Hay Yield (dry matter production) and Water Use in Millimeters per Day for Six Locations De Wit (1958).

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ATTACHMENTS

1 The Life of the Green Plant, Arthur W. Galston, Peter J. Davis, Ruth L. Satter

2 Agricultural Ecology, Joy Tivy

3 Agricultural Crop and Livestock Reports, Agricultural Commissioner

4 Crop Reports and Irrigated Acreage, Imperial Irrigation District

5 Focus on Forage, Wisconsin Team Forage

6 History, Importance, and Production Dynamics of Alfalfa in California, Dan Putnam

7 Yield Response to Water, Food and Agricultural Organization of the United Nations

8 A Guidebook to California Agriculture, University of California

9 Soil Science, The Effect of Differences in Soil-Moisture Status on Plant Growth: A Review and Analysis of Soil Moisture Regime Experiments, G. Stanhill

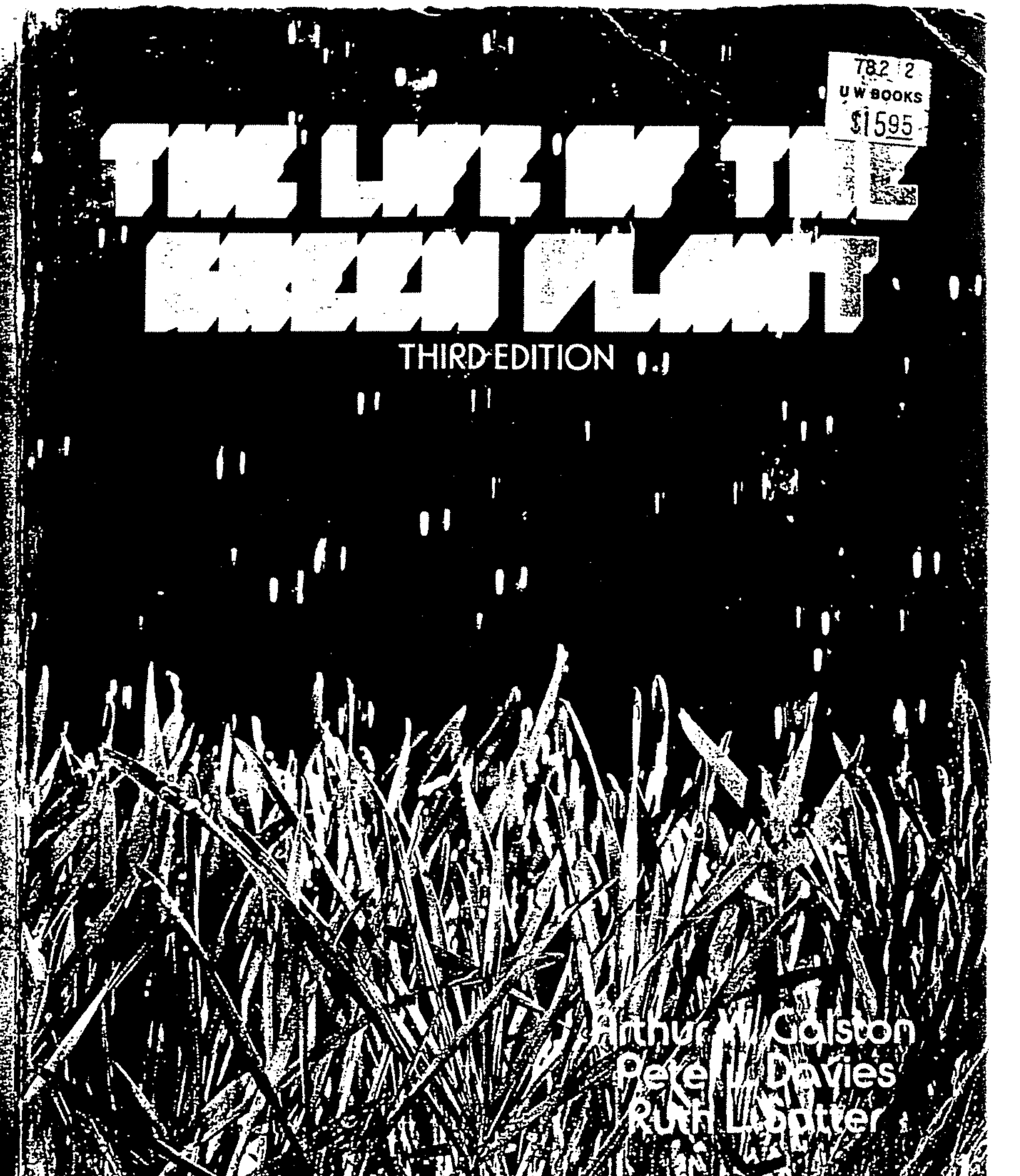
10 Transpiration and Crop Yields, C.T. DeWit

11 Relationships Between Plant Growth and Transpiration, Rodney J. Arkley

12 Functions to Predict Effects if Crop Water Deficits, H. Ian Stewart and Robert M. Hagan

Attachment 1

The Life of the Green Plant
Arthur W. Galston, Peter J. Davis, Ruth L. Satter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Photosynthesis: the Storage of Energy

Like all higher organisms, the green plant uses sugar and other oxidizable organic molecules as its source of energy, but unlike most organisms, the green plant is *autotrophic* (self-feeding). Plants make their own food, chemically converting atmospheric carbon dioxide to sugar and related substances by means of radiant energy absorbed in the photosynthetic apparatus of the chloroplast. They are thus the primary producers in nature and are independent of any external supply of organic molecules.

Some of the photosynthetically produced sugar molecules are almost immediately converted to large polymeric starch molecules and stored as starch grains in the chloroplast or leucoplast, while others are translocated from the plastids to other parts of the plant. When stored as starch, sugar is temporarily removed from further metabolic transformations, but starch can be broken down again to sugar, which is then readily oxidized to provide energy for future needs. In this chapter, we shall consider the mechanisms employed by the plant in synthesizing sugars from CO_2 and H_2O.

Photosynthesis: An Overview

When light of appropriate wavelengths is absorbed by a chloroplast, carbon dioxide is chemically reduced* to sugar, and gaseous oxygen, equal in volume

**Reduction* consists of the addition of electrons, whereas *oxidation* is the removal of electrons from a compound. Once the electron is transferred, a proton may also follow, the to the CO_2 reduced, is liberated. The direction of these changes is exactly the reverse of those accomplished during the oxidation of foodstuffs in the process of respiration, and, indeed, plants are important in the balance of nature because they restore to the air the oxygen needed for respiration by most organisms. Using the formula (CH_2O) to designate the basic unit of the carbohydrate molecule (six of these units would yield $C_6H_{12}O_6$, or glucose), we can write the equation for photosynthesis as:

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \xrightarrow{\text{Light energy}} \underset{\text{Carbohydrate}}{(CH_2O)} + \underset{\text{Oxygen}}{O_2}$$

Notice that all participants in and products of this reaction contain oxygen, and that the equation as written does not indicate whether the oxygen released in photosynthesis comes from CO_2 or H_2O. For many years biologists believed that light energy splits the CO_2 molecule and transfers a C atom to H_2O to form (CH_2O). However, this assumption was challenged by experiments with photosynthetic microorganisms, whose biochemical pathways are analogous to those of higher plants, yet different. For example, photosynthetic purple bacteria utilize H_2S instead of H_2O for photosynthesis, producing sulfur instead of oxygen as a byproduct:

$$CO_2 + 2H_2S \longrightarrow (CH_2O) + H_2O + 2S$$

The sulfur thus deposited may represent an important natural source of elemental sulfur found in various parts of the earth. The sulfur could only have been derived from H_2S, which must thus have been split during photosynthesis. Similarly, certain algae can be "trained" to use hydrogen gas, H_2, instead of water to reduce CO_2 to (CH_2O), the level of carbohydrate:

$$CO_2 + 2H_2 \longrightarrow (CH_2O) + H_2O$$

In both these schemes, it is clear that light energy is used to split (photolyze) the hydrogen donor, and that the reducing power thereby generated is used to convert CO_2 to (CH_2O).

If any common pathway of photosynthesis exists in different creatures, these studies made it seem likely that light energy splits the H_2O molecule during photosynthesis in higher plants. The essential correctness of this view became apparent when biochemists used H_2O or CO_2 labeled with isotopic oxygen (^{18}O instead of ^{16}O) in studying photosynthesis. They were able to demonstrate that the kind of oxygen released always corresponds with the

---

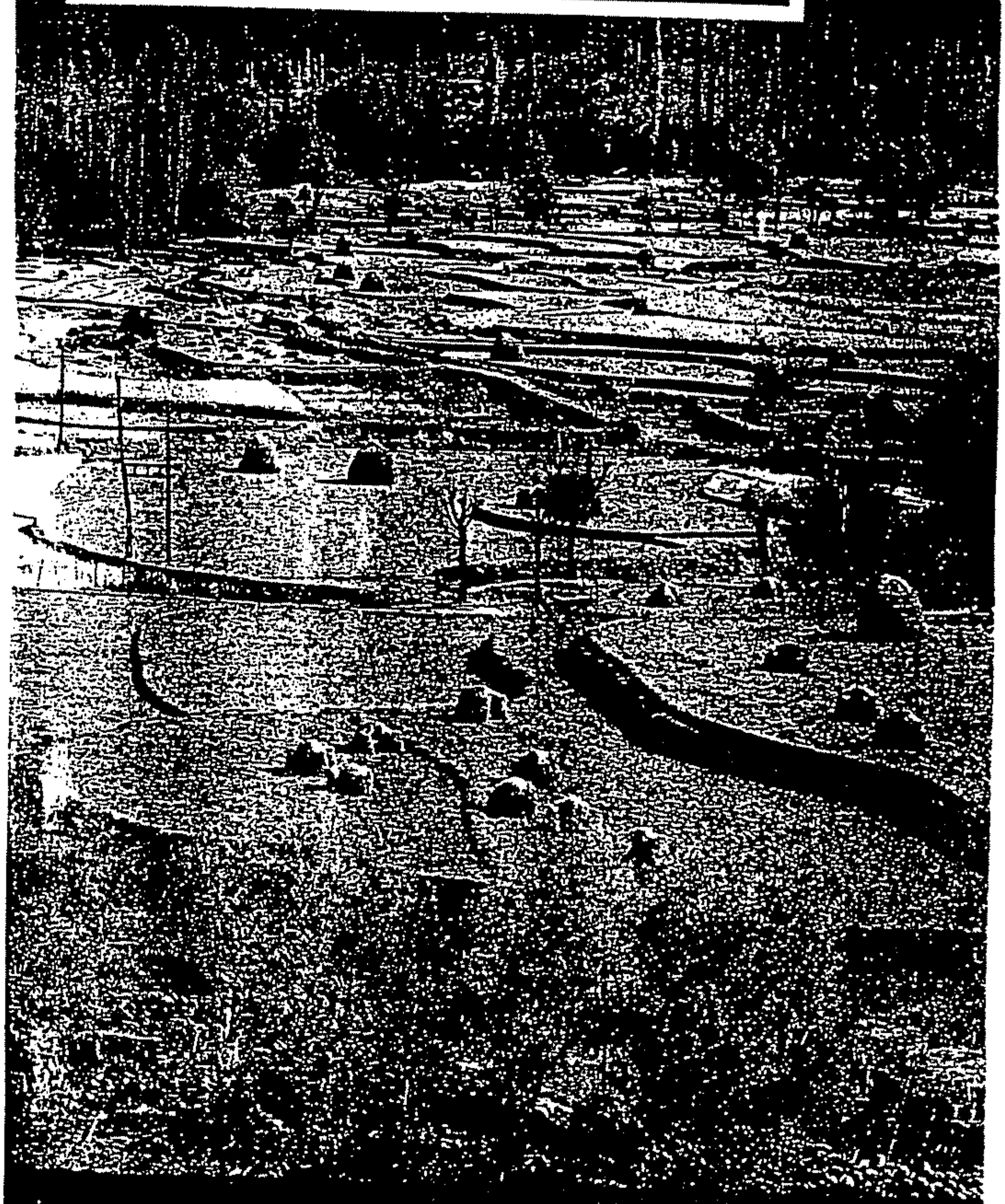
net result being the addition of hydrogen during reduction and its removal during oxidation. Oxygen is the usual final electron acceptor, or oxidizing agent, but oxidations can occur that do not involve oxygen *per se*.

Attachment 2

Agricultural Ecology
Joy Tivy

AGRICULTURAL ECOLOGY

Joy Tivy



Chapter

6

Agricultural productivity

In both unmanaged ecosystems and agro-ecosystems biological productivity is expressed in terms of the rate of plant and/or animal biomass accumulated per unit land area within a specified time period. In both it is a function of the same basic process – photosynthesis – whereby simple inorganic elements (carbon, oxygen, hydrogen, nitrogen, potassium, phosphorus) derived from the atmosphere and the soil are converted, by chlorophyll-carrying plant cells using light energy, into complex organic compounds (carbohydrates, proteins, fats). In both types of ecosystem the rate of plant growth (*net primary productivity*; NPP) is dependent, on the one hand, on the efficiency with which the available solar radiation is intercepted and used; and, on the other hand, on the difference between the rate of photosynthesis (*gross primary productivity*; GPP) and the rate of *respiration* (R) during which the energy used in plant metabolism is dissipated as heat, i.e.

$$\text{NPP} = \text{GPP} - \text{R}$$

Net primary production is usually recorded as the weight of dry matter production per unit area per unit time.

Net primary production in any ecosystem provides the food base for secondary (consumers and decomposers) production. One of the principal aims of agriculture is to channel as much as possible of the energy from incoming solar radiation into selected crops and/or livestock, and to minimize that used by such potential competitors as weeds and pests. As a result food-chains are shorter and the resulting food-web is simpler in most agro-ecosystems than in completely unmanaged systems. It is, however, very difficult and not very illuminating, to compare the net primary productivity of the unmanaged with that of the agricultural ecosystem. First, there are few measures of total biological productivity, including root biomass, for crops. Secondly, productivity or *yield* in agro-ecosystems refers to the *utilizable part* of the plant, which is not the same in every crop. Further, the utilizable part is always less than the total biological production (see Table 6.1). Then, as Loomis and Gerakis (1975) point out, not only are agricultural yields very variable, they rarely

reflect exactly either the crop or the environmental potential. This is because of the cultural and economic constraints on crop choice and the need to minimize risks.

HARVEST OR CROP INDEX

The proportion of the 'recoverable' crop yield which contributes to the final *utilizable* or *commercial yield* is commonly known as the *harvest* or *crop index*, i.e. the ratio of commercial to recoverable yield. In the case of cereals this may be expressed as the grain to straw or the grain to stover (maize) ratio. The harvest index varies widely depending on whether crop yield is a function of a vegetative or a reproductive stage of growth (Table 6.2). In the former case, which applies to tubers, roots, green vegetables and forage grasses, the harvest index is usually relatively high. It can range from 85 per cent in main-crop potatoes, close to recoverable yield in forage grasses, to less than 50 per cent in cereals, grain-legumes, cotton and oilseeds (15–25 per cent). The index can also vary within a particular cultivar or crop strain depending on density of planting, or on variations in the supply of nutrients and water. In addition the index is usually based on the *harvest at maturity*, which is normally less than that immediately before harvest, because of respiration and leaf losses. Finally, the harvest index can be a function of management. Indeed, there has been a marked increase in recent decades in the index of cereal cultivars, without a significant increase in their total recoverable yield (see Table 6.3). This is a result of a number of factors. One is the use of growth-regulating hormones, such as the chemical chlormequat, to produce a shorter stem. Another is deliberate breeding of crops with shorter stems, reduced tillering and larger flower-heads which mature earlier. The extent to which the stem and/or leaf can be reduced is limited by the minimum requirements of the plant for mechanical support and by the optimum leaf-area index for light interception. Reduced plant height also makes for greater susceptibility to disease, poor threshability and lower competitiveness with weeds (Sharma and Smith, 1986).

CROP YIELD

Crop yield is a function of a more complex set of interacting variables than is primary biological production in the unmanaged ecosystem. These include:

1. The environmental conditions under which the crop is grown.
2. The yield potential of the particular cultivar.
3. The management of the crop and its environment in order to minimize environmental constraints on the realization of the maximum yield potential of the crop.

The *environmental conditions* that control the rate of growth and the accumulation of organic matter are the same in all plants (see Fig. 6.1). Of these, the amount of incoming solar radiation available for photosynthesis and the efficiency with which it can be intercepted and used are usually considered to be the ultimate factors determining the maximum primary biological productivity that can be achieved.

Table 6.1 Contribution of various vegetative organs (minus roots) of three cereals to biological yield

	Percentage biological yield		
	Winter wheat	*Spring barley*	*Oats*
Leaves	9	6	7
Stems	33	28	34
Vegetative tillers	8	5	3
Chaff	10	10	15
Grain	40	51	41

(from Donald and Hamblin, 1976)

Table 6.2 Approximate proportion of crop that is represented in harvestable yield

	Harvestable yield (%)•
Wheat	54–60
Perennial ryegrass (at one harvest)	63
Maize	42
Field peas	50
Lettuce	50–90
Brussel sprouts	30

• Harvestable yield dry matter is presented as a percentage of total above-ground plant dry matter.

(from Spedding, 1975)

Table 6.3 Harvest index in old and new cereal cultivars•

	Crop components of yield		
Crop and location	*YR (tonne ha^{-1})*	*YC (tonne ha^{-1})*	*Harvest index (%)*
Wheat (UK)	11.00 (12.72)	2.59 (4.38)	23.50 (34.40)
	8.56 (10.02)	2.35 (3.61)	29.69 (36.00)
Barley (UK)	11.04 (10.86)	4.38 (5.21)	39.71 (48.00)
Rice (Philippines)	16.50 (17.50)	2.76 (4.18)	16.80 (24.10)
Maize (Uganda)	17.70 (18.66)	2.49 (3.69)	14.00 (19.70)
Sorghum (N. Nigeria)	39.90 (13.70)	2.66 (4.81)	7.10 (35.10)

• Results for new varieties given in parentheses.
YR = recoverable biological yield; YC = grain yield.

(from Holliday, 1976)

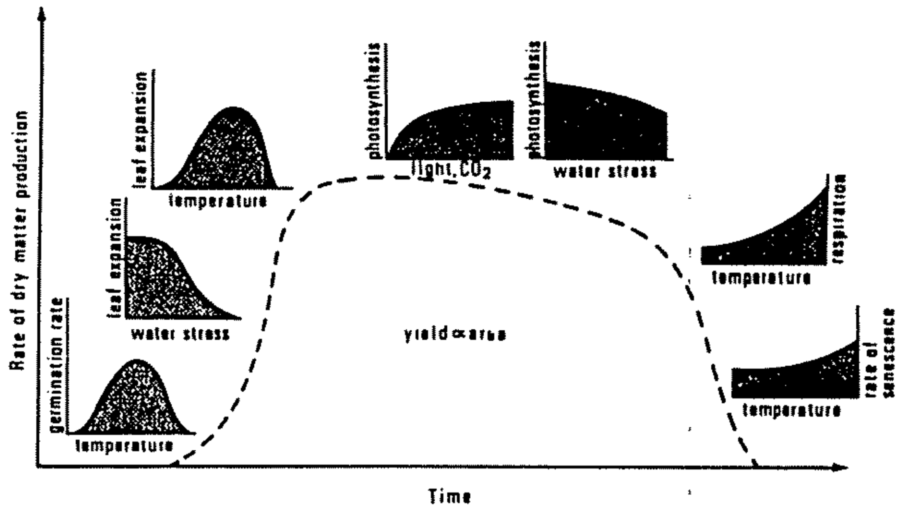


Fig. 6.1 Hypothetical relationship between the seasonal rate of dry-matter production of a crop, the physiological processes involved and environmental conditions (redrawn from Monteith, 1965)

However, temperate plants grown in full sunlight generally attain their maximum photosynthetic rate before light saturation is reached. This is because the supply of atmospheric carbon dioxide is not sufficient to allow maximum light use. It has been suggested (Monteith, 1972b) that the recent increase in atmospheric carbon dioxide

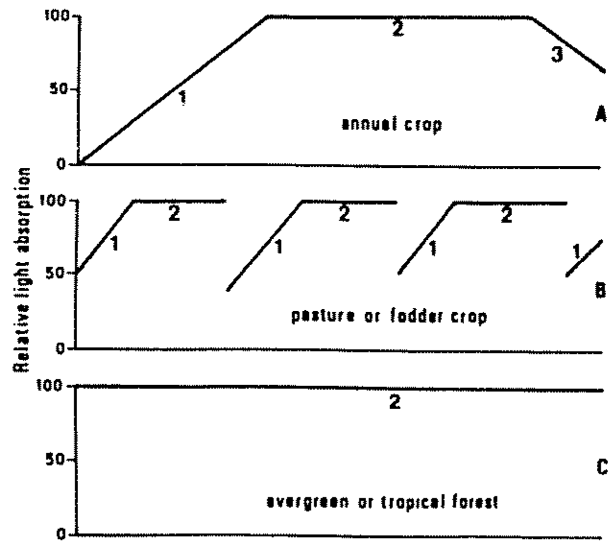


Fig. 6.2 Schematic representation of growth stages in different kinds of crops: 1) Stage in which part of incoming light energy reaches the soil; 2) Stage of closed green crop; 3) Stage of senescence (leaf discoloration or leaf fall) (from Alberda, 1962)

concentration resulting from the combustion of coal, oil and gas has been such as to allow a potential increase in the rate of biological production of the order of 15–20 per cent. The amount of light intercepted is a function of the size, structure and duration of the crop canopy (Monteith and Elston, 1971) and, more particularly, of the ratio of total leaf surface area to ground surface area, i.e. the *leaf-area index* (LAI) (see Fig. 6.2). It has been calculated that indices of 4–7 (according to the morphology of the crop) are required to intercept most of the incident light; and, at a LAI of 4–5, over 80 per cent of the available light will be intercepted by the crop canopy.

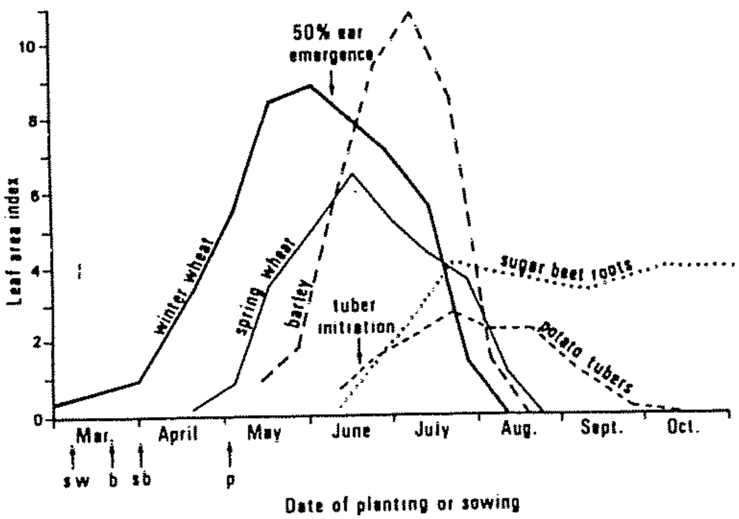


Fig. 6.3 Changes in relation to date of planting or sowing in the leaf-area index (LAI) of different crops (from Watson, 1971)

The time needed for the optimum LAI to be reached is dependent on the rate of germination (in annual crops) or of the initiation of new shoots (in perennial crops), and on the subsequent rate of leaf growth (see Fig. 6.3). The date and rate of germination are primarily controlled by soil temperatures, provided soil moisture conditions are optimal. Thereafter the rate at which leaves expand, when the LAI is low, is also an important factor in total crop production over the whole growing season. Initially growth rate (dry-matter production) is directly related to the percentage of light intercepted and to temperature (see Fig. 6.4). Once the crop canopy is complete, the rate of growth is a function mainly of temperature, assuming an adequate supply of water and nutrients. Above a minimum threshold (0.05 °C for temperate, 10–15 °C for tropical crops) the rate of growth increases exponentially to an optimum at 20–30 °C (with a lower optimum for temperate than for tropical crops). Thereafter the growth rate decreases as respiration increases at a rate which exceeds that of photosynthesis.

Total biological production by the crop is dependent on the extent to which a closed canopy can be maintained during the climatically favourable growing season.

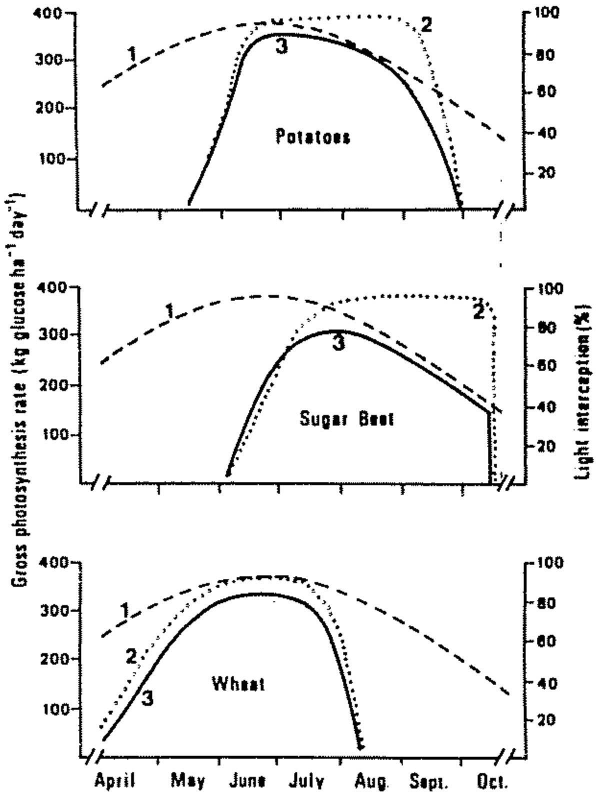


Fig. 6.4 1) Potential gross photosynthetic-rate curve; 2) Percentage light-interception curve; 3) calculated actual gross photosynthetic rate curve for potatoes, sugar-beet and wheat (from Sibma, 1977)

In many crops, and particularly those with a determinate growth habit, leaf production stops just before flowering (see Fig. 6.3) and thereafter photosynthesis depends on the persistence (duration) of existing green leaves. In contrast, indeterminate plants such as potatoes and sugar beet can continue producing new leaves for as long as the growing-season conditions are favourable. The final utilizable or economic yield then depends on how much of the assimilated material is produced in, and/or accumulated by, the yield organ.

On the basis of where and when the economic yield is finally located, Bunting (1975) distinguished three phenological categories of crop plants:

1. Yield produced throughout much or all of the growing season because it consists of the vegetative parts of a perennial or biennial crop (e.g. fodder grasses and other forage or silage crops, sugar cane, many roots and tuberous crops, taro, cocoa, rubber, tea, sago). In these essentially 'vegetative' crops the accumulation of yield in the source organs (i.e. leaves, stem) or in storage organs (e.g. tubers, roots etc.) can proceed over a long, indeed an almost indefinite, period provided growing conditions are suitable.

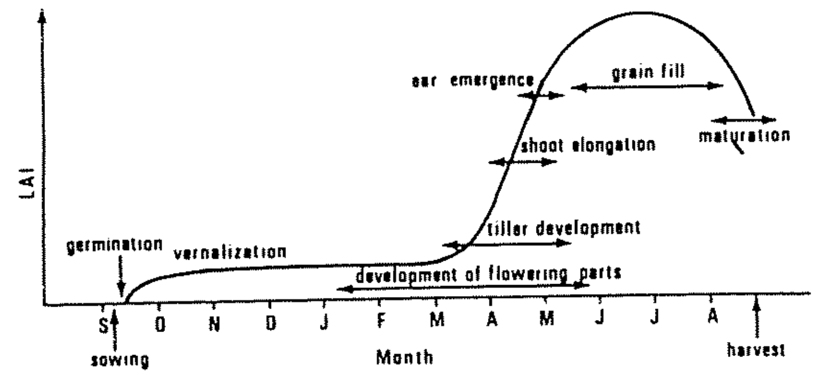


Fig. 6.5 Schematic representation of leaf-area index (LAI) with growth phases in a cereal crop (supplied by A. Williams)

2. Yield produced during a greater or lesser part of the life of the crop in fruits or seeds that begin to be formed relatively early in the plant's life (e.g. grain-legumes, oil-seeds, tomatoes, cotton, fruit trees, bush fruits).
3. Yield produced in terminal or late-formed inflorescences as the final phase in the life of an annual crop (cereals) (see Fig. 6.5) or the annual shoot in a perennial crop (e.g. bananas, plantains). As is illustrated in Fig. 6.6 most of the yield in the small grains is produced in the last-formed *flag-leaf* and in the ear over a period of only some 6–8 weeks; and the economic yield is half or less (6 tonne ha^{-1}) that in root crops (12–15 tonne ha^{-1}).

The total weight of dry matter laid down in the crop is dependent on the size of the photosynthesizing surface (LAI), while the rate of production of the economically important yield organs (e.g. the harvest index) is a function of the length of the yield-forming phase. To achieve maximum yield in a given thermal regime, the crop must have an adequate supply of water and plant nutrients during its period of growth and development. A deficiency of either can limit potential yields.

LIMITING FACTORS

Water is considered the single most important factor limiting crop yields on a global scale; and agriculture is still the major 'consumer' of water in the world today. Maximum photosynthesis occurs when the plant stomata are wide open, a condition dependent on a continuous supply of water to keep the guard cells turgid, and is normally attained when soil water is near, but just below, field capacity, i.e. when the soil water deficit is at a small but finite value of approximately 2.5 cm (Monteith, 1977). Above this threshold, leaching of nutrients or poor soil aeration can become limiting. A water deficiency which checks early growth and canopy development can curtail the total biological production over the whole growing season. Potatoes require the soil to be at field capacity during the period of development of underground organs; in the determinate cereals, whose yield is dependent on the

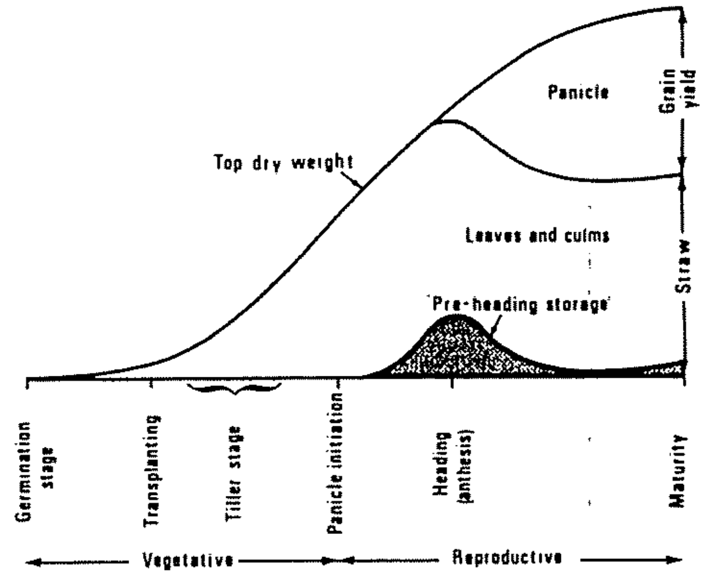


Fig. 6.6 Growth stages in rice: changes in the amount of temporarily stored carbohydrates (preheading storage) and the dry weight of various parts according to growth stages (from Murata and Matsushima, 1975)

number of grains per unit area, the critical growth phase when yield can be seriously checked by a water deficit is just before and during flower formation (i.e. anthesis). For those crops whose economic value is a function more of fresh than of dry weight, a water deficit during their production phase may be sufficient to effect a reduction in the size (or weight) class by which they may be graded for sale.

The efficiency with which crops use water is usually expressed as the ratio of dry weight produced to water used (see Table 6.4). While *water-use efficiency* varies with the other environmental conditions (including diseases) that affect yield, some crop varieties are more efficient in this respect than others, C4 crops generally being twice as efficient as C3 crops. One of the aims of agricultural management is to increase the water-use efficiency of field crops. Over the last 50 years efficiency has doubled in wheat, barley, rice and cotton and has increased five times in maize and soy. This is mainly the result of fertilizer application at a rate greater than the water consumption of the particular crop. Breeding early-maturing varieties or those adapted to cooler or drier growing conditions has also contributed to higher water-use efficiency; for example cotton that matures in 120–130 days after planting is 25 per cent more efficient than a variety that requires 150–180 days (Begg and Turner, 1976)

A deficiency of one or more nutrients can, under otherwise favourable conditions, limit yield; and the limiting nutrient will be that with the largest suboptimal deficiency. This is the basis of the *Law of the Minimum* first propounded by the agricultural chemist Leibig in the nineteenth century. There are still many parts of the developing world where low crop yields are related, in part, to deficiencies of phosphorus and nitrogen, particularly in old, highly weathered and leached soils

Table 6.4 Water requirement of crop plants (g water used per g dry matter produced)

Sorghum	322	Soya beans	744
Maize	368	Sweet clover	770
Wheat	513	Vetch	794
Oats	597	Potatoes	636
Rice	710	Cotton	646
Flax	905	Sugar beet	397

(from Spedding, 1975)

which have developed on acid igneous rocks, or sandstones. In the developed countries of the world, optimum nutrient levels on crop land are maintained by a continual and still increasing input of fertilizers, and more particularly of nitrogen; in many, potassium and phosphate levels are now roughly stable and the status of most soils in respect of these nutrients is adequate.

Soil fertility, however, is dependent not only on nutrient status but on the ability of the soil to supply nutrients and water to crop roots at a rate commensurate with uptake. The amount of available nutrients and water is dependent on the physical condition of the soil, particularly its cation exchange capacity and water-holding capacity. Management of the soil by tillage, fertilization, and drainage or irrigation aims to enhance, as far as possible, the physical fertility of the soil. Actual crop yields will depend on the degree of adaptation that can be achieved between the crop requirements for maximum yield and the environmental resources available.

There is also a close relationship between water stress and nutrient deficiency. Nutrient levels in the soil are usually highest near the surface, which is also that part of the soil which dries out first. Hence reduced growth when there is a moderate water deficiency may, in part, result from a reduction in uptake of nitrogen and phosphorus. Conversely, soil nutrient status can affect water use. High nitrogen levels stimulate vegetative growth – the demands of which may lead to soil water deficits that reduce yields to below those that might have occurred as a result of low nitrogen levels (Cooper, 1975).

Crop yield is, however, very variable both spatially and temporally and the two main causes of variation are:

1. The so-called 'negative' biological factors.
2. The weather.

The *negative biological factors* are the weeds, pests and pathogens – which comprise the third major organic component of all agricultural ecosystems. They are the unwanted and agriculturally unproductive 'enemies of the farmer'. More precisely, they are, from the farmer's point of view, plants (weeds), animals (pests) and pathogens which have the potential, when their populations reach or exceed a certain threshold, to reduce the quantity and/or quality of crop or animal yields and to increase costs of production. Weeds and pests depress yields either indirectly by competing for resources, reducing crop and livestock health, or directly by the consumption of agricultural products.

WEEDS

The number of weed species is very small when compared with the total world flora and a high proportion belong to a few families of flowering plants. In eastern North America seven families contribute 60 per cent of the 700 species of introduced weeds. While many are herbaceous, some of the rangeland weeds are woody.

Weeds of agricultural land have several sources of origin, including:

1. Open, disturbed habitats in which only those plants adapted to unstable conditions can survive, such as natural coastal or riverine habitats and man-made sites such as road and rail cuttings, ditch and canal banks; gravel workings etc.
2. Relatively undisturbed woodland or grassland habitats which contain species capable of growing more vigorously in agricultural habitats because of lack of competition for light.
3. Exotic species introduced accidentally or deliberately from other environments.
4. Cultivated species which have 'escaped' from gardens.
5. Crop-seed contaminated by weed seed.

The most successful weeds, which cause the greatest crop losses, are those plant species particularly well adapted to take advantage of and grow more vigorously in the man-made, man-disturbed agricultural habitats than they would elsewhere. While agricultural weed plants share many morphological and physiological characteristics, common to all is the ability to survive on open disturbed land. This facility is closely related to the high reproductive capacity combined with rapid growth and establishment, characteristic of the majority of weeds. Many are annuals with a short life-cycle, and a rapid and relatively high seed production (even under poor environmental conditions) which is spread over a long period. Dormancy is variable but, nevertheless, many weed seeds can remain viable for a relatively long time buried in a cultivated soil. Hill (1977) notes that 47 per cent of the seeds of shepherd's purse (*Capsella bursa-pastoris*) germinated after 16 years; 84 per cent of the greater plantain (*Plantago major*) after 21 years and 83 per cent of the black nightshade (*Solanum nigrum*) after 39 years. In addition, many weed seeds can survive and germinate successfully in open exposed sites subject to wide ranges of day and night temperatures.

Flexibility of seed production undoubtedly contributes to a high survival rate, even in the face of intraspecific competition, and to resistance to the rapid environmental changes common to the agricultural habitat. Many of the more serious and difficult weeds are perennial plants with particularly well-developed powers of vegetative reproduction from surface or underground food-storage organs such as stolons or rhizomes whose growth can be stimulated by fragmentation during cultivation. Some of the most successful perennial weeds are grasses, e.g. common couch or quake grass (*Agropyron repens*), Johnson grass (*Sorghum halpense*) and wild oat (*Avena fatua*).

Another characteristic of the successful weed is its adaptation for both long and short-distance seed and/or vegetative dispersal. This includes forms which facilitate transport by wind, water or attached to animals or within the faeces of animals. However, the close association of the weed and the crop plant has inevitably resulted in man being, directly or indirectly, the most important agent of weed dispersal today. Weeds are widely and rapidly dispersed as contaminants in crop seed, in hay, silage and other animal feedstuff, and in straw; on agricultural machinery and vehicles; in packaging materials; and in the bulk movement of sand, ballast and soils. A very considerable number of agricultural weeds (e.g. chickweed (*Stellaria media*), knotgrass (*Polygonum aviculare*), charlock (*Sinapsis arvensis*) and annual meadow grass (*Poa annua*)) now have a virtually cosmopolitan range. The efficiency of the weed dispersal, however, is largely a function of the viability and longevity of its seed.

Weeds in general exhibit a wide range of tolerance to variations in the physical environment and are well adapted to survive in disturbed cultivated habitats, fully exposed to extremes of temperature and to rapid variations in surface moisture conditions. Others can take advantage of the more favourable microclimate provided by the growing crop. Indeed the success of many weeds is related to the adaptation of their growth forms and development patterns to that of the crop they infest and, more especially, to their ability to survive the particular method of cultivation being used. Many show a high degree of 'mimicry' of the associated crop, e.g. grass weeds in cereals and pastures. An annual such as winter wild oat (*Avena ludiviciana*) can infest winter-sown wheat because it can become established before the wheat crop is tall enough to shade it out in the spring. Again, weeds with a short life-cycle can grow and produce seed before or even between cleaning and cultivation. In contrast, weeds of improved and/or cultivated hay pastureland are often avoided by livestock because, for one reason or another, they are unpalatable; and as a result they have a competitive advantage over the grazed plants. However, as Hill (1977) points out, the relative aggressiveness of a particular weed depends on the type, stage and management of the crop on the one hand and on the prevailing environmental conditions such as weather and soil type on the other.

It has been suggested that weeds may have beneficial aspects in their contribution to soil organic matter, reduction of soil erosion and concentration of nutrients which deeper rooted species may help to recycle. These benefits, however, would probably be more than outweighed, from an agronomic point of view, by the fact that they frequently harbour actual or potential crop pests. In fact most insect pests also feed on wild plants, particularly when the latter are closely related to the crop; and weeds provide a source of pest food particularly when the crop growing period is shorter than that of the insect feeding season and as a result ensure a reservoir of crop pests and disease.

PESTS AND PATHOGENS

The pests and pathogens of crop plants are the unwanted 'consumers' in all agro-ecosystems. The largest group of pests is that comprising the *insects* and *mites* of which the majority are plant-eaters. It has been estimated that 500–600 species attain pest status in the USA. Population numbers (particularly of insects) living in the soil and in the air are enormous – 25 million per hectare of soil and 22 million fly larvae per hectare of oats are not unusual figures. Reproduction rates and population growth can, given favourable conditions, be extremely rapid. The cabbage aphid, for example, has the potential to produce a new generation every 2 weeks.

Some of this group of pests are *generalists* in their feeding habits, others are more *specific*, attacking only a limited number of closely related plants. Indeed many of the pest insects common on cultivated plants in many parts of the world are monophagous. Some inflict direct damage or destruction, others are more significant as disease vectors. The economic importance of pest damage is closely related to the type of crop concerned. As Wigglesworth (1965) has pointed out, plants with an indeterminate flowering habit are generally subject to attack over a longer period than are those with a determinate habit. Hence crops like cotton, coffee and deciduous fruits require a greater amount of pest control than those such as maize or the small grains.

Another large group of pests is composed of the *nematodes*, microscopic non-segmented eelworms, which inhabit the soil and usually eat underground plant parts. They tend to be more prevalent in warmer climates, though the most important is probably that causing 'root-knot', which is cosmopolitan in range. Other pests are the *snails* and *slugs* and some *vertebrate* animals – mostly small mammals such as rodents and birds, though the emu and the red kangaroo, which have attained pest status in Australia, are among the larger animals in this category.

The *pathogens* are the disease-causing micro-organisms, which include:

1. *Fungi:* responsible for the greatest number and diversity of plant diseases. Most agricultural crops are susceptible to fungal disease and some can be infected by as many as thirty different species.
2. *Bacteria:* account for relatively few crop diseases though some have, at various times, caused exceptionally severe damage.
3. *Viruses:* infect almost all the higher plants.

The pests and pathogens of crop plants originate in much the same way as do weeds, either by co-evolution with the ancestors of modern crops or by deliberate or accidental transport from a known to an alien environment where the natural constraints on population numbers do not operate. In both instances, however, increase of a population to the level of an agricultural pest is related to a greatly increased supply of high-quality crop food grown under optimal climate conditions for pest reproduction, combined with a drastic reduction, or even absence, of natural predators. Reduction of natural enemies of the pest is usually the result of one or more of the following factors:

1. Introduction of the pest into an alien habitat where natural predators either do not exist or, if introduced, cannot tolerate the new environment.
2. Alternation of different crops (sometimes with fallow periods), which may create a time-lag between the introduction of a new crop and immigration of predators.
3. The greater susceptibility of predators to pesticides and other toxic substances used on the farm than that of the 'target' pests.
4. Natural predators may have alternate prey or adult food requirements other than crop pests.

In addition, high crop densities favour the even spread of comparably high pest populations before intraspecific competition and predator immigration can begin to take effect. A unique characteristic of crops is that they exhibit an almost universal specificity of particular pathogens; relatively few diseases affect different crop species. The crop pest/pathogen problem has increased with the modern trend in arable farming towards long-term monocultures, particularly of crops with a relatively long maturation period, a high degree of genetic uniformity and where climate and/or irrigation favour continuous cultivation of the one crop. The problem is further exacerbated by the rapid evolution of insecticide resistance in organisms with large populations and short life-cycles, and continuous breeding of ever-more pest- or disease-resistant crops which in turn may stimulate the evolution of more virulent pests and pathogens.

Table 6.5 Percentage of global preharvest losses due to weeds, insects or diseases

	Percentage total loss			*Weight (million tonnes)*		
	Maize	*Wheat*	*Rice*	*Maize*	*Wheat*	*Rice*
Causes of loss						
Weeds	37	40	23			
Insects	36	21	58			
Diseases	27	39	19			
Total loss preharvest (L)				121	86	207
Harvested crop (H)				128	266	232
$L/(L+H) \times 100$	35.7	24.4	47.1			

(from Spedding, 1975)

It has been estimated that weeds, pests and pathogens may account for a reduction of global preharvest yields by nearly 50 per cent in some crops (see Table 6.5). All depress yield mainly by reducing the LAI of the crop with which they are associated. Weeds also compete with the crop for incident light and nutrients and, particularly in the early growth stages, can reduce yields drastically. Agricultural soils may contain a considerable store of viable weed seeds, some of which were originally sown with the crop; some a residue from a previous crop; others imported from other areas. Cultivation and crop rotation were traditionally the most effective methods of weed control. Greater specialization accompanied by a reduction in the use of rotations together with an increase in continuous arable monoculture has resulted in a greater carryover of weeds, pests and pathogens in arable soils. Poor quality grass-seed has within the last 5–6 years created increased weed problems in Britain. The expansion of winter cereals on to formerly improved grassland has been accompanied by a rapid spread of weeds, particularly of black grass (*Alopecurus myosuriodes*), soft brome (*Bromus mollis*) and wild oats (*Avena fatua*).

Pests and pathogens reduce yield directly by consuming or spoiling the harvestable organ or indirectly by decreasing the size or effectiveness of the leaf area. Control now relies heavily on the use of chemical pesticides and the breeding of disease-resistant cultivars. Both methods have, however, created almost as many problems as they have been designed to solve. The rapid rate of reproduction and evolution of ever-more chemical-resistant pests and pathogens has necessitated the concomitant breeding of even more resistant crops. Pesticides can reduce or completely destroy natural pest predators as well as the target pest organisms themselves. Additionally, some chemicals are more persistent than others and can be taken up from the soil by plants and incorporated in food-chains with deleterious effects on organisms other than the target species. More recently, with increasing knowledge of entomology and the factors controlling insect populations, there has been a revival in the use of biological methods of control. These include encouraging or introducing suitable predator species, and endeavouring to maintain, by careful monitoring and management, a high diversity of insects with low self-regulating population levels, more akin to those in wild ecosystems. The most developed approach to the problem is to use all methods available with varying emphasis for different crops at different stages in their growth cycles. This is the basis of what is known as *integrated pest management*.

WEATHER

Finally, yields vary depending on the *weather conditions* at each growth phase of the particular crop up to, and including, the maturation of the harvestable part of the plant but, more particularly, during the most critical phase. All other factors being satisfied, maximum yield will depend on the occurrence of optimum temperature, light, and soil water levels during each development stage. Depression of yield due to bad weather will depend on when it occurs and how severe the limitations are or by how much and for how long the actual conditions deviate from the optimum. Crops whose economic yields comprise the bulk of the above-ground vegetative production (i.e. green vegetables) are particularly susceptible to water deficits throughout the year. For the cereals the critical phase is just before and during flower formation (anthesis). Water deficiency is critical for soft fruits during the production phase. Suboptimal temperatures retarding growth are most serious in the earlier crop phases; and low temperature combined with high precipitation and low sunshine levels can delay maturation, and reduce the quantity and quality of both cereals and fruit.

Biscoe and Gallagher (1978) have noted that the processes of vegetative growth and grain production are independent in cereals. As a result the effect of weather on dry-matter production *per se* does not seem to exert a direct influence on the rate of grain growth. Except under very high temperatures and severe water stress, mean grain weight is relatively constant and yield is a function more of the number of grains produced per unit area. However, water stress 5 weeks before ear emergence in wheat can result in a 70 per cent decrease in grain yield but only a 52 per cent decrease in total dry-matter production; comparable figures given for maize are 47 per cent and 30 per cent respectively.

Although understanding of the relationships between crop yield and weather has increased considerably in recent decades, efforts to establish a statistical relationship between yield and particular weather components have failed to produce consistent results; and empirical hypotheses are difficult to substantiate in the field. Hudson (1977) has suggested that one of the ways to assess the relative importance

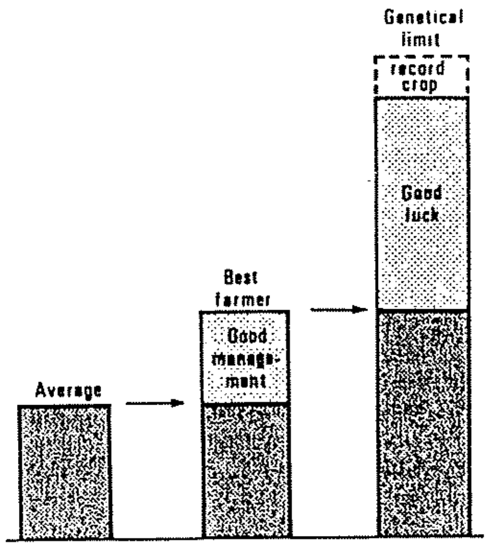


Fig. 6.7 Increases in yield due to good management (from Hudson, 1977)

of the effect of weather is to compare average and record yields in particular localities as shown in Fig. 6.7.

INCREASE IN CROP YIELD

Before the agricultural revolution of the eighteenth century, crop yields everywhere were very low compared with those achieved today. Grain yields of only 0.25 tonne ha^{-1} were recorded in medieval Britain (Evans, 1980). With the enclosure of land and the application of new farming techniques, agricultural production began to rise. New methods of cultivation – particularly crop rotations and the use of the 'grass-break' – helped to depress weed competition while ensuring the build-up and conservation of soil fertility. Towards the latter half of the nineteenth century, traditional nutrient sources such as marl, bonemeal, manure and sewage began to be supplemented by mineral fertilizers. In addition, new varieties, particularly of wheat, better adapted to the newly opened agricultural land in the subhumid climatic areas of America, Eurasia, Australia and South Africa, were being developed. By the end of the century, yields were showing a marked upward turn (see Fig. 6.8). This was seen earliest in Japan, the Netherlands and Denmark, where apart from the drought years there has been a steady increase in cereal yields since the beginning of the century. However, all the agriculturally developed countries shared in the dramatic increases in crop yields following the Second World War consequent upon a high and continuing input of fertilizers, pesticides and insecticides and the development of crop varieties with high yield potentials. It has been estimated that world fertilizer consumption has increased about five times since 1945, and that 36–55 per cent of the present yield of the four main arable crops in Britain (barley, wheat, potatoes,

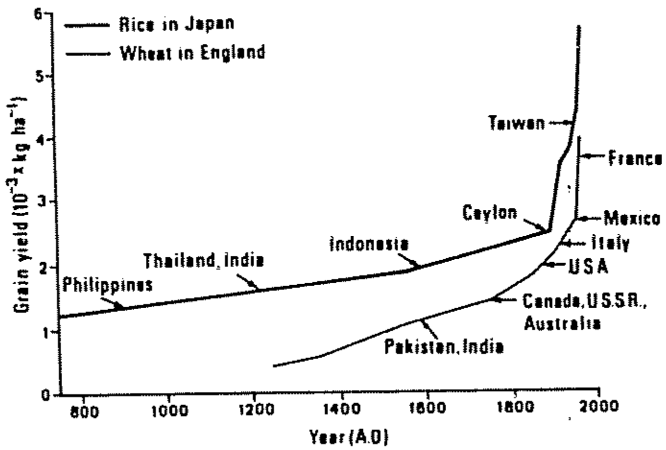


Fig. 6.8 Historical trends in the grain yield of rice in Japan and of wheat in England compared with 1968 yields of rice and wheat in selected countries (from Evans, 1975)

sugar beet) is the result of fertilizer input (Hood, 1982). As Table 6.6 indicates, increase in the use of nitrogen has been most marked and sustained; that of phosphorus and potassium has stabilized at levels necessary to replace loss by cropping.

Table 6.6 Fertilizer usage in the UK

	Fertilizer usage (k tonne)		
Year (June to May)	*N*	*P_2O_5*	*K_2O*
1939–40	61	173	76
1949–50	229	468	238
1959–60	410	458	430
1969–70	796	476	419
1979–80	1268	440	444

(from Hood, 1982)

The production of new higher-yielding cereal varieties was effected by the long-established process of pure-line selection, by which means desirable characteristics are selected from existing varieties, self-fertilized and propagated until a true breeding strain is developed. A major breakthrough was achieved with the production of hybrid maize by cross-fertilization of different varieties. It came into commercial production in the USA in the 1920s and 1930s and by the 1950s had been adopted throughout the Mid-West Corn Belt, where yields increased five-fold in 20 years. Hybrid maize has a very high yield potential, but it does not breed true and its cultivation is dependent on the use of new seed each year, produced by specialized seed-banks. It is also genetically uniform in comparison to the more variable 'land-races' and cereals produced by pure-line selection and consequently it has less resistance to unfavourable environmental conditions. Maize, because of the morphological separation of its male and female organs and natural cross-pollination, was easier to hybridize than the small-flowered self-pollinating cereals such as wheat, barley and rice. The application of hybridization to improved yield potential in these crops came later and was the basis of the Green Revolution of the 1960s.

THE GREEN REVOLUTION

The success following the Second World War of plant-breeding programmes aimed at increasing crop yields in the agriculturally underdeveloped tropical areas of the world gave rise to the term *Green Revolution*. The aim of the programmes was to produce varieties – particularly of wheat and rice – which would be capable of high yields: the HYVs as they became known. The traditional 'unimproved' varieties of these crops were tall, with long lax leaves, a low harvest index and deep widely spreading root systems. Yields were exceptionally low, being limited by poor soil fertility and, more particularly, a deficiency of nitrogen, which is greater in the Tropics than elsewhere. These low yields, however, were to a certain extent compensated by the high genetic diversity of varieties that had evolved by selection over a very long time and which gave an inbuilt resistance to drought or disease. Higher yields could not be attained by increasing planting density because of the lack of nitrogen and the depressive effect of greater leaf-shading, while increased use of fertilizers merely resulted in greater leafiness and mutual shading together with elongated flower-stems which became increasingly susceptible to lodging (Jennings, 1974). The principal outcome of the Green Revolution was to produce dwarf or semi-dwarf varieties of cereal crops with stiff stems and short upright leaves which allowed dense planting, with minimum shading and relatively constricted root systems, and the potential to give high yields when supplied with adequate fertilizers, water, and disease protection (see Fig. 6.9).

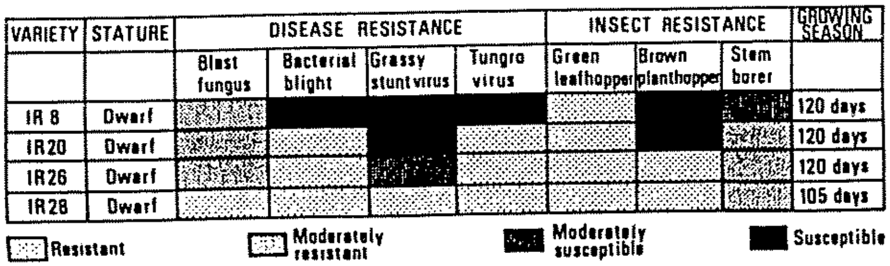


Fig. 6.9 Characteristics of rice varieties produced by IRRI breeding programmes (illustration by A. Christie from Jennings, 1976 by courtesy of *Scientific American*)

The breeding programme started in Mexico in 1943 with the improvement of spring wheat. Yields in the Tropics were, on average, 750 kg ha^{-1} in 1940; by 1970, 3200 kg ha^{-1} were being produced and seed was exported to India, Pakistan and Turkey. In 1960 the International Rice Research Institute (IRRI) initiated research on rice and in 1966 the very first successful new variety – IR8 – was released for use in the Philippines. It was high-yielding, insensitive to day-length and adaptable to a wide range of environmental conditions. Maturing in 100–120 instead of 160 days, it could produce two crops in one year. Other varieties followed and the need to produce those which combined disease and drought resistance with high yield increased: in gaining the latter, the new genetically uniform strains of rice lacked the resistance to environmental hazards of the traditional varieties. Further, as Jennings (1974) notes, the impact of disease, insects and weeds on agriculture is very much greater in the Tropics than elsewhere. Also, new varieties retain their competitiveness for only about half the time they would in temperate climatic areas. Hence the crop breeders have an even greater struggle in the Tropics than elsewhere to keep pace with fast-evolving pests and pathogenic organisms.

Agricultural research in the developing countries is conducted by a network of international institutes in co-operation with national research programmes (see Table 6.7). Each of the institutes is concerned with particular crops (or livestock) and some of them confine their interest to a particular region or climatic regime. All the crop-research institutes employ an interdisciplinary approach in which plant breeders, plant pathologists, entomologists, economists and others work together to improve the productivity of crops. Since 1971 the institutes have been funded in large measure by the Consultative Group on International Agricultural Research (CGIAR), which is an association of national governments, specialized agencies of the United Nations and private philanthropic foundations.

The products of the Green Revolution did not prove to be the hoped-for panacea to the agricultural problems of the developing countries. Their cooking quality and palatability were not the same as those of traditional rice varieties and they were, as a result, less acceptable to subsistence farmers. Also, the cultivation of the HYVs required high inputs of fertilizers, water, herbicides and pesticides, the cost of which was far beyond the means of the small farmers. Hence the new varieties made a greater impact on the more affluent and larger landowners than on those whose need for food was greater.

MAXIMUM YIELDS

There are indications that some of the highest yielding types of crops are approaching the maximum limits set by biological constraints. Potential yield for a given crop can be estimated, given the annual radiation regime, the percentage of light intercepted by the leaf canopy and the harvest index (see Table 6.8). Average annual *record yields* on experimental farms are indicative of the highest possible yields that have been attained by a given crop in a particular environment under the currently most advanced technology and management. Average farm yields, in both developed and developing countries of the world, still represent only a relatively small

Table 6.7 International agricultural research institutes in developing countries

Institute	*Areas of research*	*Funded location*
International Rice Research Institute (IRRI)	rice	1960 Philippines
International Maize and Wheat Improvement Center (CIMMYT)	wheat, maize, barley tritical	1966 Mexico
International Institute of Tropical Agriculture (CIAT)	corn, rice, cow peas, soya beans, lime beans, root and tuber crops	1969 Colombia
International Potato Centre (CIP)	potatoes	1972 Peru
International Crop Research Institute for the Semi-arid Tropics (ICRISAT)	sorghum, millet, chick peas, pigeon peas, ground nuts	1972 India
International Laboratory for Research on Animal Diseases (IRAD)	livestock diseases	1973 Kenya
International Livestock Centre for Africa (ICLA)	African livestock	1974 Ethiopia
International Centre for Agricultural Research in Dry Areas (ICARDA)	wheat, barley, lentils, broad beans, oil-seed, cotton	(Planned) Lebanon

(from Jennings, 1976)

Table 6.8 Actual and potential cereal yields in the UK

	Yield (tonne ha^{-1})	
	Winter wheat	*Spring barley*
Estimated potential yield (Austin, 1978)	12.9	11.1
Record yields obtained (Hood, 1982)	12.0	10.0
National average yield 1979–80 (HGCA, 1980)	5.2	4.1

(from Reece, 1985)

percentage of record yields. However, in some crops such as temperate cereals, record yields are beginning to approach potential yields (Fig. 6.10). To date, increase in yield potential has been achieved by extending the period over which there is a complete crop canopy in order to increase the amount of radiation intercepted; and by increasing the harvest index. The latter has made a very significant contribution to increased yield of cereals. In some cases an index of 50–60 per cent has been achieved; but the maximum limit cannot exceed 60 per cent because any further reduction in the proportion of assimilating organs would be insufficient to maintain a higher harvest index.

The ultimate biological constraint on increased yield is the photosynthetic efficiency of the crop, i.e. the ratio between the solar energy intercepted and the energy of the dry matter produced. It can be expressed by a number of different parameters: time (annual to daily); insolation (total or visible); output (energy equivalent to dry weight, of the total or part of the plant); the economic/utilizable yield in the case of a crop. Efficiency varies with species. Under optimum environmental conditions of high temperatures and light intensities C4 crops which are adapted to more temperate climatic conditions are more efficient than C3 cultivars. In any species, efficiency can, however, vary during the growth period from *c.* 0.18 per cent to *c.* 2.88 per cent, with low values at the beginning and at the end. High-yielding crops grown under optimum environmental conditions may attain a maximum daily efficiency of 10 per cent. On the basis of maximum daily values crops appear to be more efficient than uncultivated plants. However, a comparison of conversion rates over the available growing season (Table 6.9) reveals that only in exceptional cases do crop efficiencies exceed 2 per cent; at best they are comparable to temperate forest efficiencies in Britain.

However, efficiency in terms of economic yields is very much lower, of the order of 0.3–0.4 per cent. Evans (1975) has pointed out that, while agricultural land represents about 11 per cent of the world's terrestrial surface, harvested products account for less than 1 per cent of the total primary biological productivity. Further, actual efficiency is low compared to estimated values of potential efficiency: annual dry-matter production even for a 'good' crop of grain or sugar is less than 3 per cent while the theoretical maximum photosynthetic efficiency is 18 per cent. These comparatively low efficiencies of primary biological productivity in crops are to a considerable extent the price paid for economic production (Alberda, 1962). They reflect energy losses which are incurred in the process of diverting incoming energy along a few selected food-chains. Many crops are annuals whose growth period is less than the potential growing season available; light energy is 'lost' at the beginning because of an incomplete canopy and low temperatures (and/or water stress) and at the end because of leaf senescence as well as, in certain plants, the use of energy in the process of translocation of material to storage organs. Many crops are grown in supraoptimal (for carbon dioxide availability) light intensities. Many are grown over a much wider range than their wild progenitors and, hence, are more subject to reduction of productivity as a result of water, heat and/or nutrient deficiencies. Alberda (1962) records results of experiments which give growing-season efficiencies, for grass and sugar beet grown with ample water and nutrients, ranging between 5 and 6 per cent of insolation (wavelength 400–700 μ). These are compar-

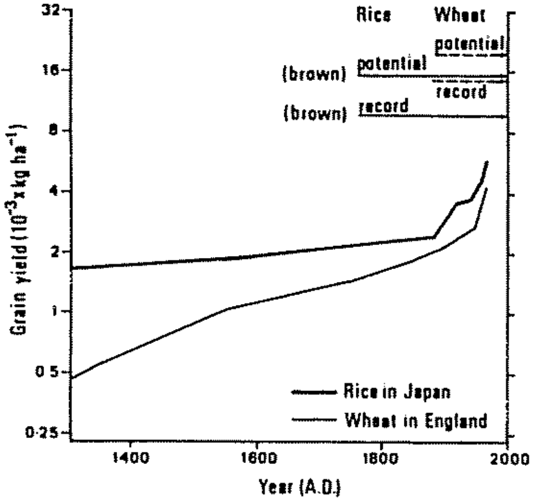


Fig. 6.10 Historical trends in rice yields in Japan and wheat in England. Potential yield ceilings are those estimated for 400 cal cm^{-2} day^{-1} during grain filling. The vertical axis is on a logarithmic scale in all cases (from Evans, 1975)

Table 6.9 Comparison of photosynthetic efficiency for types of vegetation and selected cultivated crops

Crop or ecosystem	*Location*	*Growth period (days)*	*Photosynthetic efficiency (%)*
Natural ecosystems			
Tropical rainforest	Ivory Coast	365	0.32
	Denmark	180	
Pine forest	UK	365	1.95
Deciduous forest	UK	180	1.07
Crops			
Sugar cane (March) (C4)	Hawaii	365	1.95
Elephant grass (C4)	Puerto Rico	365	2.66
Maize (two crops) (C4)	Uganda	135+435	2.35
Maize (one crop) (C4)	Kenya (uplands)	240	1.37
Soya beans (two crops) (C3)	Uganda	135+135	0.95
Perennial ryegrass (mean of six C3 cuts)	UK	365	1.43
Rice (C3)	Japan	180	1.93
Winter wheat (C3)	Holland	319	1.30
Spring barley (C3)	UK	152	1.49

(from Cooper, 1975)

able to calculated potential production rates of a close green surface grown under environmental conditions.

MULTIPLE CROPPING

To date, plant-breeding programmes have concentrated on increasing the yield of single-crop stands per unit land area. There are, however, indications that the rate of this process is beginning to slow down. Given the continuing need, particularly in the developing countries, for increased food production, attention has turned to the possibilities of intensifying production by the development of *multiple-cropping systems*.

Multiple cropping involves the production of two or more crops from the same land unit (field) in the course of one growing season (or year, where the two are synonymous), thereby intensifying cropping in both time and space. The crops may be grown simultaneously, i.e. intercropped, or as a sequence of single crops, i.e. sequentially.

The principal cropping patterns within these two systems (Andrews and Kassam, 1976) are:

1. *Sequential cropping*
   (a) Double, triple, quadruple cropping;
   (b) Ratoon cropping, i.e. taking a crop from growth of shoots or seeds after harvest.
2. *Intercropping*
   (a) Mixed intercropping with no distinct row arrangement;
   (b) Row intercropping with one or more crops planted in distinct rows;
   (c) Strip intercropping in different strips wide enough to permit independent cultivation but narrow enough for crops to interact agronomically;
   (d) Relay intercropping during part of life-cycle of each crop; a second crop is planted after the first has reached its reproductive stage of growth but before it is ready for harvest..

Multiple cropping is a very ancient method practised throughout the world and is still the most widespread method of cultivation in the humid tropical countries with a long rainy season and an irrigated agriculture. It varies in form with geographical and energy gradient from very complex intercropping where there is a year-long growing season to sequential and eventually single cropping as the limiting factors of moisture and temperature increase in severity and duration; and from very high labour intensity on small farms (i.e. 5–7 ha) to increasing capital inputs with increasing size, mechanization and crop specialization (Sanchez, 1976). In Zaria Province (North-Central State, Nigeria) Norman *et al* (1984) recorded up to 156 different types of crop mixtures involving two to six crops – those with 2 accounting for 15 per cent; 3 for 42 per cent; 5 for 23 per cent and 12 for 5 per cent respectively of the intercropped area. The most frequent crop mixtures were:

Millet/sorghum
Millet/sorghum/groundnut/cow pea
Millet/sorghum/groundnut
Cotton/cow pea/sweet potato
Cotton/cow pea
Millet/soya bean/cow pea
Soya bean/groundnut

The success of intercropping depends on the ecological compatibility of the crops involved and the extent to which they complement or compete with each other in the use of available environmental resources. Interspecific competition can be minimized by a variety of strategies which include (Harwood and Price, 1976):

1. Using mixtures of similar growth form but of different maturation time (e.g. millet 3 months; sorghum 6 months).
2. Stratification of crops of different potential height as in the case of:
   (a) Annuals planted under tree crops such as coconut, rubber, oil palm etc.;
   (b) Short-season crops which are planted at the start of the growing period of long-duration crops (i.e. corn or soya bean, with sugar cane);
   (c) A mixture of annual crops of differing height, with the tall (corn; cassava) harvested before the short crops (sweet potato); or the short (mung bean) after the taller (corn).

One of the most important advantages of intercropping is the potential for increasing the yield per unit area over that obtained from a single-stand crop grown on the same area (see Table 6.10). It has been estimated that yield can be of the

Table 6.10 Yields of grain by pure and interplanted stands of corn and pigeon peas

	Grain yield (kg ha^{-1})		
Treatment	*16 weeks**	*24 weeks†*	*24 week total‡*
Corn	3130	–	3130
Pigeon pea	–	1871	1871
Mixed intercrop	2025	1710	3735
Row intercrop	2606	1854	4460

* Corn harvest; † pigeon-pea harvest; ‡ corn and pigeon-pea harvest.

(From Oelsligle *et al*, 1976)

order of 20–50 per cent more when the mixture is one of annual plus perennials. In addition, intermixed crops can provide mutual support (as when vine forms use upright cereals) and protection from exposure to high-intensity rainfall, direct insolation and high wind force. A more complete vegetation cover protects the soil

from the accelerated erosion to which all bare mineral soils are susceptible, particularly in the humid Tropics. This also helps to suppress weeds, while the high diversity of crops maintains low pest populations. Also, all types of multiple cropping provide a wide variety of food over a longer period than short-season single cropping and help to reduce the risks of complete harvest failure due to unseasonable weather during the growing season. However, the application of scientific principles and modern agricultural techniques to developing further the production potential of multiple cropping is difficult not only because of the complexity of traditional systems but also because they are based on inherited experience.

The development of early maturing HYVs has begun to increase the flexibility of multiple cropping, particularly of sequential cropping; and in those areas of India where only single cropping could be undertaken this has facilitated double cropping. With a rapidly maturing sorghum replacing the traditional photosensitive *kharif* (wet season) varieties, a second *rabi* (post wet-season or residual moisture) crop can be successfully introduced; or the existing *rabi* crop can be planted earlier and as a result give a higher yield. Multiple cropping was much less frequent in temperate areas of the world where the growing season can be severely limited by low temperatures and frost as well as by low rainfall. In more humid areas, however, it was much more common in the older pre-industrial types of farming when grain mixtures (corn) were often grown. More recently double-row and/or sequential two-crop systems have evolved. The availability of herbicides, the development of shorter season cultivars of small grains and soya bean, and the adoption of minimum- or zero-tillage techniques now allow the speedy establishment and successful maturation of a second crop. This is exemplified by the cultivation of soya beans after wheat or barley in the humid South-East USA (see Table 6.11). Similarly in

Table 6.11 Double-cropping systems practised in South-East USA

Winter crop	*Summer crop*
Small grains (wheat, barley, oats) for	Corn (grain/silage)
grain-production	Soya beans
silage	Sorghum (grain/silage)
hay	Sorghum – Sudan grass
grazing	Millet
green crop	

(From Lewis and Phillips, 1976)

parts of Western Scotland early potatoes lifted in June are followed by a high-yielding 'catch crop' of rapid-growth hybrid ryegrass which can provide a cut of silage or hay or be grazed until the end of the growing season in September/October. However, as Oelsligle *et al* (1976) note, it is in the dryland areas of the developing world that the potential for multiple cropping is greatest and most needs to be developed.

AGROFORESTRY

One particular form of multiple cropping is that termed *agroforestry* (MacDonald, 1982). This is a system of land use which combines the cultivation of trees with other crops and/or livestock, either partially or sequentially, and produced both for food and a tree product. The term is relatively recent though the particular type of cropping it defines is very old. In many parts of the developed world, trees are still integral components of the farm systems. The traditional agro-ecosystems of the humid Tropics are frequently characterized by an intimate mixture of trees with perennial and annual crops, all of which provide food and income. The most intensive agroforestry system is that of the Sri Lankan Kandy 'gardens'. These are small farms based on a close association of coconut, kitril and betel palms; with cloves, cinnamon, nutmeg, citrus, durian, mango, rambutan and bread fruit; a lower stratum of bananas and pepper vines; and a peripheral ground layer of maize, cassava, beans and pineapples. As such, this combination provides the farmer with a constant food supply and an income dispersed throughout the year and gives a greater degree of stability than one or two crops. The significance of the tree crop is also related not only to the protection it affords the soil but to the maintenance of the nutrient cycle as a result of a constant supply of tree leaf litter. Indeed a major programme has been initiated in Sri Lanka to establish agroforestry on abandoned tea plantations, which are particularly susceptible to accelerated soil erosion.

Agroforestry has developed from two different forms of land use in the Tropics. One is the widespread, and until recently very stable, system of bush fallow and arable food crops. The stability of this system has been attributed to the deep-rooted trees and shrubs, many of them nitrogen-fixers, which recycle nutrients very efficiently. It is, however, being rapidly undermined by increasing population and a drastic reduction in the length of the fallow period. The second is *taungya* or forest establishment, a form of agriculture the aim of which is to maintain, i.e. conserve, forest and soil in the face of increasingly rapid deforestation. It originated in Burma as a means of using and developing shifting agriculture to re-establish forest fallow by selective tree planting. *Taungya* is now widely used in Ghana and Nigeria to solve the twin problems of land degradation and the high cost of reforestation. As with multiple cropping the ecological benefits of agroforestry include increased use of environmental resources, suppression of weeds, maintenance of soil fertility and stability, and reduction of pest problems. It is, however, debatable as to whether the annual yield of usable products is greater than in non-tree crop mixtures. Other suggested disadvantages are the high degree of interspecific competition between trees and crops and the problem of maintaining a balance between tree and crop components; the difficulties of mechanizing cultivation; and the eventual export of large quantities of nutrients when the system is cropped for wood. There has been a very considerable increase in interest in the ecological characteristics of agroforestry over the last decade. Its potential value as a form of productive land use on all marginal land and particularly as a means of regenerating degraded land in the developing countries has been widely publicized.

Chapter

7

Domestic livestock

In comparison to crops, the number of types of fully domesticated animals is relatively small (see Table 7.1). Although domestic livestock are as numerous as humans, they consume four times as much plant matter. However, while animal food (including fish and shellfish) provides only one-tenth of the world's calorific consumption, it is the source of a third of the total protein intake by human beings.

Table 7.1 The main agricultural animals of the world

Animal	*World population 1970–71 (thousands)*	*Number of breeds (approx.)*
Cattle	1 141 215	247
Sheep	1 074 677	230
Pig	667 689	54
Goat	383 025	62
Buffalo	125 412	7
Horse	66 312	124
Ass	41 914	12
Mule	14 733	

(from Spedding, 1975)

The domestic animal (i.e. bred in captivity) has an important role in all agricultural systems. Not least is its ability to convert 'second-class' or low-quality plant protein material into 'first-class' or high-quality animal protein. This is because the herbivorous animal can manufacture its own *lysine*, from lysine-deficient plant material, and produce a meat protein with a high digestibility ratio. The most important domestic animals are cud-chewing *ruminants*, which have the ability to digest plant material high in cellulose, i.e. fresh green leaves and stems. This is a function of the high bacterial content of the enlarged stomach or *rumen* – an organ often likened to a 'living fermentation vat'. As a result the domestic ruminants

Attachment 3

Agricultural Crop and Livestock Reports
Agricultural Commissioner